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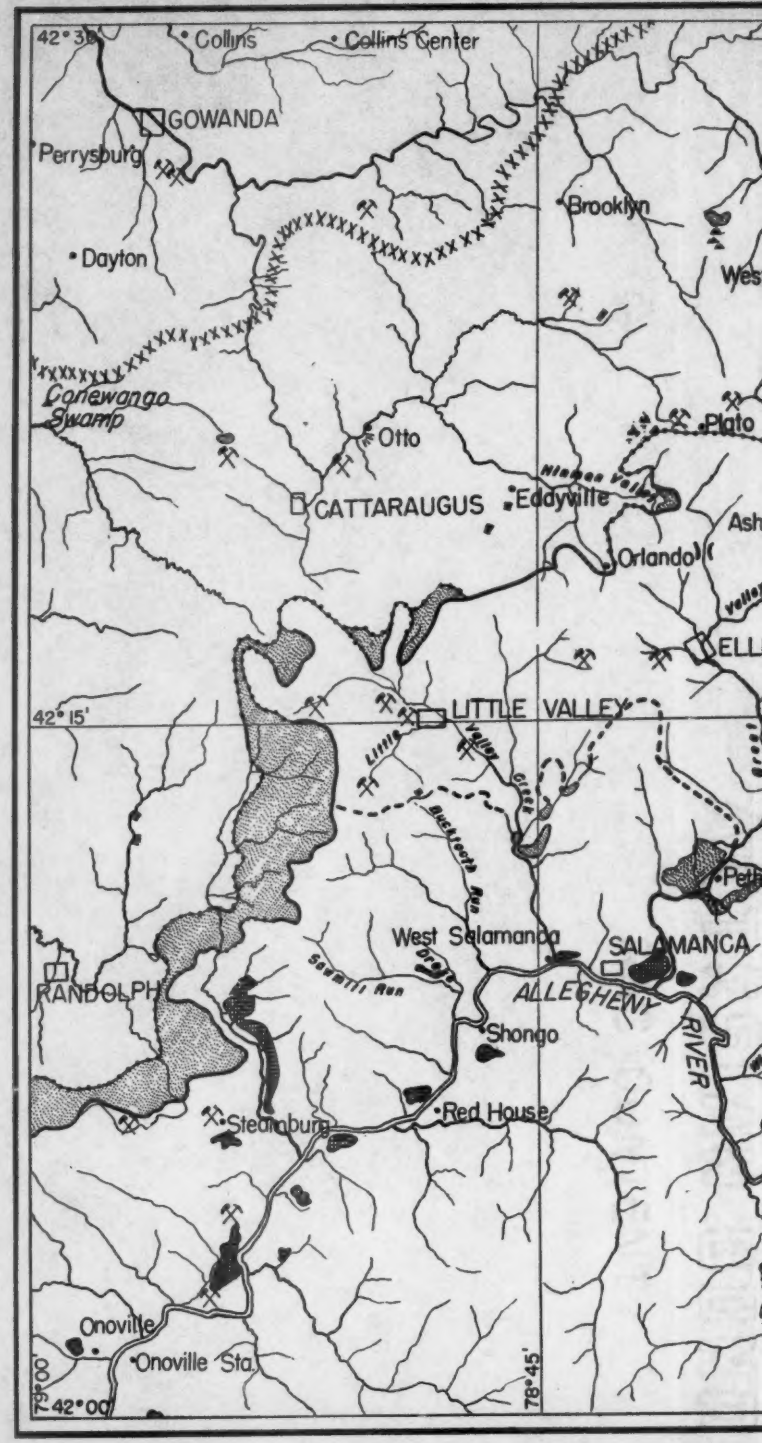
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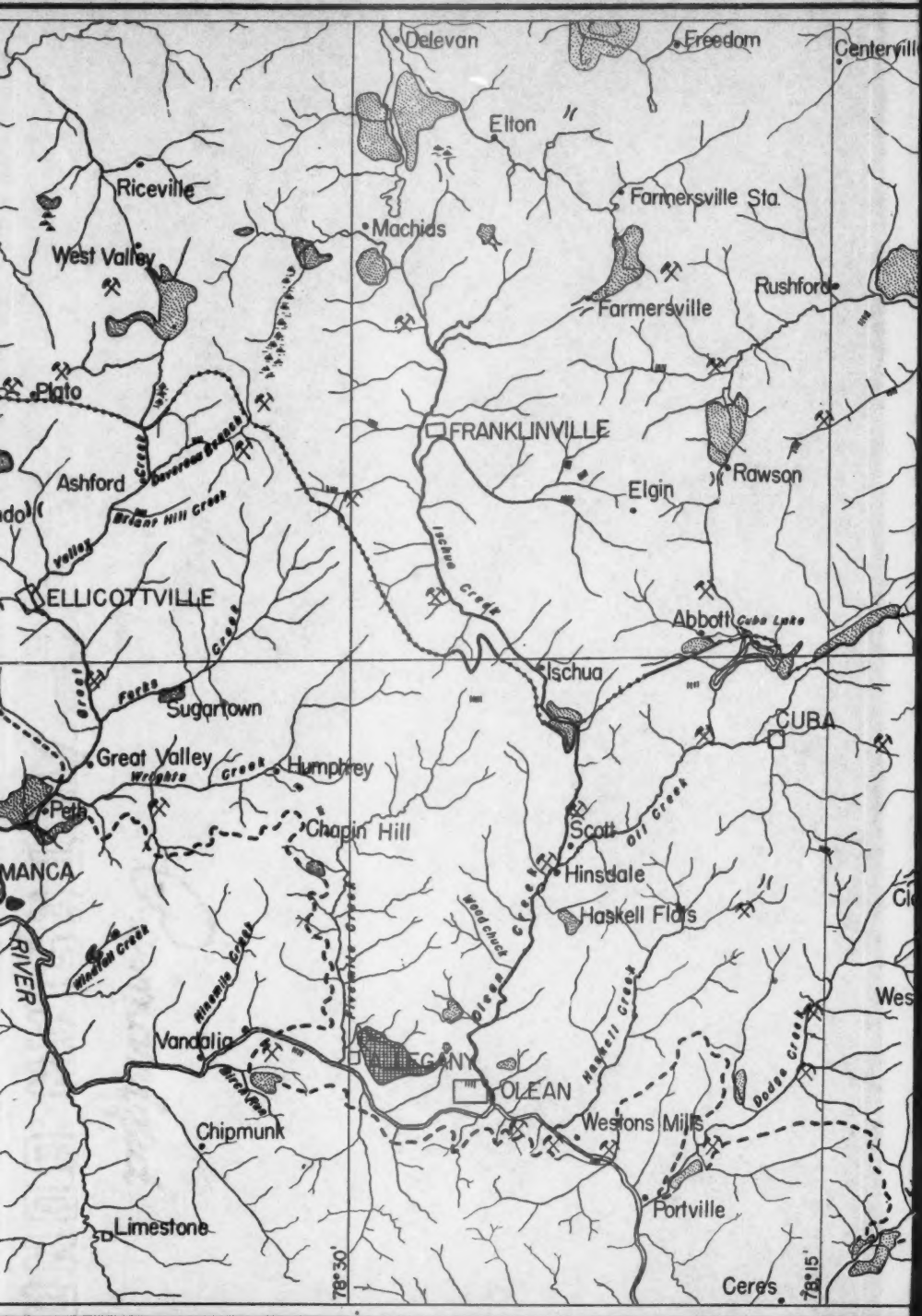
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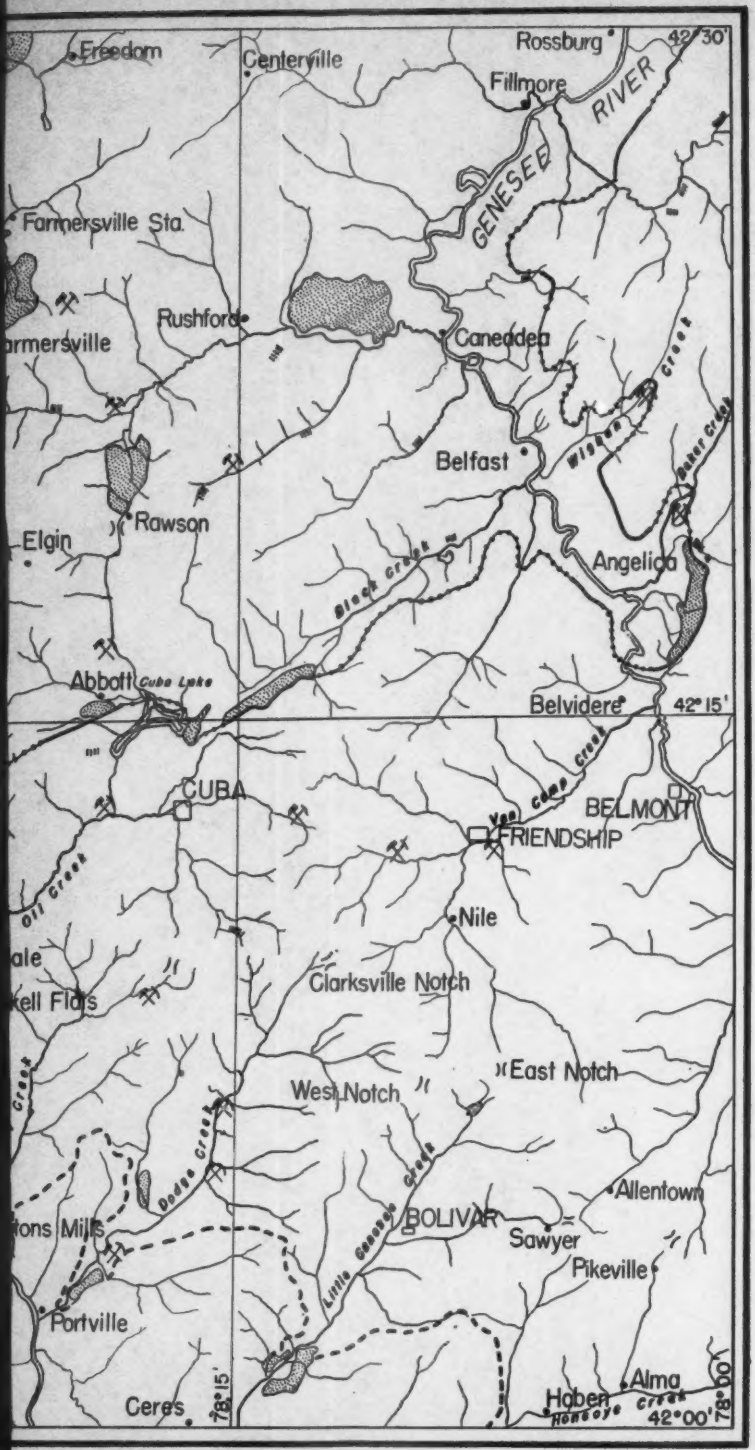

LEGEND

WISCONSIN DRIFT

XXXXXX VALLEY HEADS

BINGHAMTON

OLEAN

ILLINOIAN DRIFT

MORAINAL TOPOGRAPHY

EXPOSURE

GRAVEL PIT

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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CORRELATION OF THE DRIFTS OF THE SALAMANCA RE-ENTRANT, NEW YORK

BY PAUL MacCLINTOCK AND EARL T. APFEL

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ABSTRACT

Based primarily on lithologic differences, three Wisconsin drift sheets are recognized. The oldest is named the Olean; the middle, the Binghamton; and the youngest the Valley Heads. Beyond the Wisconsin drift border Illinoian drift is found, isolated into patches by erosion. Similar patches of Illinoian drift within the area covered by Wisconsin drift are postulated to explain the local lithologic vagaries of the latter. Olean ice, in overriding such patches of older drift, acquired material therefrom to enrich locally the younger drift in the constituents common to the older. At Otto, New York, is seen in vertical section (1) weathered Illinoian drift, (2) peat, (3) Olean drift, (4) Binghamton drift.

The Wisconsin drift forming the east side of the re-entrant is older than that forming the west side.

INTRODUCTION

PURPOSE

When the National Research Council Committee on the Glacial Map of North America undertook the correlation of published and unpublished data, it marked for review the earlier assumed correlation of the drift sheets around the Salamanca re-entrant in western New York and recommended restudy of the problem. Field work, prosecuted in that area during the summer of 1941, is the basis, chiefly, on which this report is written.

LOCATION

The area selected for intensive study lies along the southern boundary of western New York State, entirely within the Allegheny plateau province. The Allegheny River is the largest stream in the region, with its valley bottom at about 1400 feet above sea level. The tops of the hills range between 2000 and 2400 feet in elevation, giving a relief to the maturely dissected landscape of 600 to 1000 feet.

PREVIOUS WORK

The drift border has long been known from the work of Lewis and Wright (1884), T. C. Chamberlin (1883), and Leverett (1902; 1934). It has commonly been considered as the margin of one ice advance. The drift margin has a re-entrant at Salamanca, New York, and the drift at the border on the west side of this re-entrant was considered to be the same age as that on the east side, though Chamberlin suggested further study of the problem (1883).

GENERAL RELATIONSHIPS OF THE DRIFTS

Four drift sheets are identified within the area studied. They are the Illinoian and three Wisconsin sheets designated from older to younger: the Olean, the Binghamton, and the Valley Heads (Fig. 1). The Illinoian drift extends only a few miles

FIGURE 1.—*Index map of the Salamanca region*

south of the boundary of younger drift. In turn the drift of each Wisconsin substage covers more or less of the preceding drift, so that essentially the only places where one drift sheet may be studied lie between its border and that of the next succeeding drift. The border of the Illinoian drift is crossed by the Olean drift at Allegany. The Binghamton drift border crosses that of the Olean drift about 2 miles west of Little Valley, Cattaraugus County, and thus forms the west side of the Salamanca re-entrant. The youngest or Valley Heads drift was not found beyond the older drifts at any point.

ACKNOWLEDGMENTS

Field work was principally financed by a grant from the Penrose Fund of the Geological Society of America. MacClintock also received a grant from the Department of Geology of Princeton University.

Louis C. Peltier, of Bucknell University, acted as field assistant to MacClintock. He deserves special mention for helpful discussion and criticism, both in field and office, and also for supplying part of the transportation. Howard Knight assisted Apfel. The late Frank Leverett has given helpful suggestions during both the planning and the execution of the work.

Paul B. Sears, of Oberlin College, has examined the peat of the Otto exposure and has given permission to quote his findings. A. F. Buddington examined the erratics for clues of their derivation.

Federal Survey topographic maps were used for field mapping. Plate 1 is constructed on a base traced from the following quadrangles: Cattaraugus, Franklinville, Ellicottville, Angelica, Randolph, Salamanca, Olean, and Belmont. The base for Figure 1 was traced from the 1/1,000,000 map of the U. S. Geological Survey.

ILLINOIAN DRIFT

GENERAL CONSIDERATIONS

The oldest drift found in the area is that which was correlated by Leverett in 1934 with the Illinoian. It comprises both till and gravel, the latter mostly in terraces along the Allegheny Valley. This older drift is limited to isolated patches, left after Sangamon erosion had largely dismembered what may well have been a fairly continuous drift sheet. Beyond that Wisconsin drift border the exposures of the older drift, where not stripped and kept fresh by surface erosion, are deeply weathered and show unmistakable evidence of their age. However, within the Wisconsin drift border the overriding younger ice has normally stripped away the weathered part of the older drift. In these latter places on the east side of the re-entrant, the older drift is recognized by the sharp difference in lithology between it and the overlying and surrounding Wisconsin drift. The Illinoian drift contains upward of 11 per cent limestone and 2 to 7 per cent igneous material, whereas the Olean (Wisconsin) drift typically contains no more than 2 to 3 per cent limestone and less than 2 per cent igneous material. On the west side and north of the re-entrant, where the Binghamton Wisconsin drift has the same lithology as that of the Illinoian, the latter was identified at only one place. Near the village of Otto (Cattaraugus County), a layer of peat separates a lower deeply weathered drift from the overlying Wisconsin. The occur-

rences of Illinoian drift within the area of the Wisconsin need to be discussed in considerable detail for on them rests a considerable part of the argument in distinguishing between the Olean and the Binghamton drift sheets. Occurrences of till, gravel, and overridden gravel are discussed in this order.

TILL

Patches of till have been found at eight places north of the Allegheny River. Probably a more detailed survey would disclose other occurrences.

The easternmost exposure of Illinoian drift in the area occurs at the mouth of Woodchuck Hollow, 3 miles north of Olean, where a stream-cut bank shows 3 feet of dense buff calcareous till below 15 feet of noncalcareous gravel. Pebbles dug from the till showed 11 per cent limestone (Table 1). Many igneous pebbles and boulders are present in the bank though the pebble analysis does not show them. Many of the stones in the till are striated and polished. This patch of till is assigned to the Illinoian because its lithology differs strikingly from that of the surrounding Wisconsin drift and because it lies 5 miles south of the Binghamton drift boundary, with which it could have no connection, being entirely surrounded by exposures of Olean drift.

A small hillside bench 1½ miles northeast of Vandalia is about 800 feet long by 100 feet wide and 80 feet above the river. An 18-foot road cut exposes tight stony till very much weathered. The igneous stones are crumbly to a depth of 8 feet. The sticky matrix resembles gumbotil.

In Windfall Creek, 4 miles east of Salamanca, 2 miles above its mouth a much subdued and deeply weathered moraine crosses the valley. Igneous material is much weathered in the upper 5 or 6 feet. One gully at the brow of the inner slope of the moraine shows gray-mottled, buff, sticky, noncalcareous till to a depth of 12 feet. The stream has undercut the moraine in one place exposing calcareous gray till at an estimated depth of 35 feet below the top of the moraine. A mile upstream, at the branching of the creek, is a gently sloping and rounded nose of drift. The road cut exposes much-weathered sticky till to a depth of 3½ feet. Several erratic boulders were found on the divide at the head of Nine Mile Creek, and Leverett (personal communication) describes one on the upland 2 miles north of Salamanca.

In Sawmill Run, 4 miles west of Salamanca, the road cut on the riverward side of a 40-foot terrace exposes 12 feet of leached, buff, hard and compact till containing fairly well weathered igneous stones lying on 6 feet of leached silt and sand which in turn lies on 12 feet of leached gravel. The depth of weathering shows this drift to be Illinoian. Several small erratics were found, in road cuts, between here and the headwaters of this stream. At the latter place a 12-inch boulder of granite was dug from the dense drift of the road cut 3 feet below the top of the exposure. The boulder had a 3-inch weathered rind. Small erratics were dug from the roadside banks also in Drakes Run and Bucktooth Run to the north.

Both to the northeast and the southeast of Steamburg much-weathered drift is banked against the foot of the big hills, in rude terraces at 1500 feet elevation. Boulders are seen on the surface and in shallow gullies. An 18-foot road cut, 3 miles north of Steamburg, exposes 12 feet of dense, tough till, leached 10 feet and

TABLE 1—*Pebble counts*

Locality	No. of Stones	Percentage							Age
		Local sandstone, siltstone, shale	Limestone	Red sandstone	Chert	Quartzite	Gneiss	Igneous	
Allegany (NE., outskirts), Gr.	346	60	12	10	8			7	Ill.
Allegany (½ mi. N.), Gr.	207	49	30	4	6	2	3	0.5	Ill.
Allegany (½ mi. S.), Gr.	261	84	3	3	3	3		4	Ol.
Allegany (2½ mi. WSW.)	238	82	3	3	5	5		2	Ol.
Allegany (2½ W., Hornell pit), Gr.	1224	83	1	1	10			3	Ol.
Allegany (3½ mi. W.), Gr.	208	65	17	3	5	6		4	Bing.
Angelica (3 mi. NW.), Kame Gr.	225	72	17	4	2	3		2	Bing.
Ashford (½ mi. E.), till	303	81	10	1	3	4		2	Ol.
Belfast (3½ mi. ENE.), Kame Gr.	280	87	11	1		1		1	Bing.
Belfast (3 mi. SW.), till	204	75	15	6	2	1		0.5	Bing.
Caneada (2 mi. W.), Gr.	300	65	16	6	7	3		4	Bing.
Cuba (2½ mi. NE.), Gr.	314	81	12		2	2		2	Bing.
Eddyville (1 mi. S.) (Cattaraugus Q.), Gr.	134	63	20	8				9	Bing.
Elgin (1½ mi, S.) (Corry Q.), Gr.	355	79	9	5	4			3	?
Elmira (N. Y., 5 mi. W.), Gr. under T.	343	61	19	7	3	7		5	Bing.
Farmersville, (1 mi. NE.), Kame Gr.	367	73	19	2	1	2		3	Bing.
Freedom (2 mi. W.), Gr.	360	50	31	4	4	7		5	Bing.
Fillmore (5 mi. E.), till	235	96	3	2				0.4	Ol.
Friendship (2 mi. W.), Kame Gr.	278	92	2	4		1		1	Ol.
Great Valley (2 mi. W.)	179	78	6	5	4	1.6	1	3	Ol.
Ischua (2 mi. W.), Gr.	197	68	14	7	3	5		4	Bing.
Machias (2½ mi. S.), Gr.	131	55	33	5	3	2		3	Bing.
Olean, Kame Gr.	354	84	0.6	5	3	3		4	Ol.
Olean (1½ mi. SE.), Gr.	238	77	11	4	3	3		2	Ol.
Olean (2½ mi. SE.), Gr.	242	96	2			2		1	Ol.
Olean (3 mi. N.), till	274	84	11		2	2	.5	?	Ill.
Oxford (3½ mi. SW.) (Oxford Q.), Gr.	231	50	35	8.8	1.6			2.9	Bing.
Peth moraine, Gr.	218	66	26	3		3		2	Ol.
Peth Moraine, till	189	65	27	2	1	2		4	Ol.
Plato (1 mi. NE.), Kame Gr.	201	73	20	2	2	1		4	Bing.
Plato (5½ mi. WSW.), Gr.	260	88	8	2	2	2			Bing.
Portageville (3 mi. SE.) (Portage Q.) Gr.	321	77	14	1	1	2		4	Bing.
Randolph (5 mi. E-NE.), till	249	87	3		2	5		3	Bing.
Randolph (3 mi. SE.), till	300	95	2		1	1		1	Bing.
Randolph (4 mi, SSE.), Gr.	250	65	15	8	3			6	Bing.
Scott (1 mi. SW.), Gr.	313	56	25	4	4	4		6	Bing.
Scott (3 mi. N.), Gr.	242	68	22	2	0.5	5		2	Bing.
Spring Creek (½ mi. W.) (Corry Q.), Gr.	571	91	2	2	2			2	Ol.
Steamburg, Kame Gr.	344	66	15	7	7			6	Ill.
Unadilla (1 mi. SE.) (Unadilla Q.)	280	71	21	6		2		0.5	Bing.
Wellsville, Pa. (1 mi. W.) (Wellsville Q.), till	295	97	1	2					Ol.
West Valley (1½ mi. W.), Kame Gr.	245	67	19	3	4	2		4	Bing.
West Valley (4 mi. E.), Kame Gr.	357	60	17	8	6	5		3	Bing.
Westons Mills, Kame Gr.	340	96	3	0.5	2	1		0.5	Ol.

very calcareous in the lower 2 feet which lies on 4 feet of gravel containing 20 per cent limestone. This great depth of leaching, occurring where the top of the exposure is sloping so that erosion has doubtless removed some weathered material, indicates that the drift is Illinoian. At Steamburg is a hill of coarse, cobbley and bouldery gravel, layers and areas of which are so cemented by lime that they protrude as ledges from the face of a pit. The count shows 15 per cent limestone and 6 per cent igneous pebbles. Erosion has stripped material off the sharp crest of the hill as fast as it was leached for even the soil on top of the hill now effervesces with acid. The hill may be an Illinoian kame or perhaps Illinoian morainal gravel isolated and cut to its present shape by Sangamon erosion and by Wisconsin flood waters.

One mile south of Ashford on the north side of Bryant Hill Creek, Ellicottville quadrangle, the stream has undercut and exposed a 60-foot bank of blue-gray till, containing igneous boulders in large number and variety. There is, likewise, a considerable percentage of limestones, but slumping had so confused the exposure that an uncontaminated sample for pebble analysis could not be taken. Since this exposure lies outside the Binghamton drift border and is entirely surrounded by exposures of Olean drift, it is here tentatively considered to be Illinoian.

On the east side of Little Valley Creek at West Salamanca a big fresh highway cut, on the riverward side of a terracelike mass of drift, exposes till and gravel. The exposure is difficult to interpret because in the steam-shovel operations material from below has been plastered on the sloping bank and incorporated with upper material. But after half a day's study and digging the relations seem to be as shown in Figure 2. At the west, gravel lies on calcareous till. In the center, yellow weathered gravel lies on 3½ feet of leached till on 30 feet of calcareous till, which is relatively low in limestone and igneous material but contains a great abundance of well-striated stones and angular fragments both of local bedrock. This till lies on weathered orange-colored sand, bearing much-weathered igneous stones, in the eastern part of the exposure. The orange sand lies on buff and blue-gray till. The weathered gravel is doubtless Illinoian, but the till with its relatively low limestone content might be either Illinoian till which, at its extreme border, acquired enough local bedrock material that its richness in limestone and igneous matter became diluted to the extent observed, or it may be Olean drift of Wisconsin age with a normal content of igneous and calcareous material. Because of the position here outside the Olean drift border and because of the large number of angular fragments of local bedrock in the till, the whole deposit is referred to the Illinoian.

GRAVEL

A series of gravel terrace remnants are present in the Allegheny Valley. Those 10 and 20 feet above mean river level are of Wisconsin age as judged by relatively slight dissection and weathering, but the higher ones, 50 to 100 feet above river level, as judged by the same criteria, are Illinoian. At Salamanca, on each side of the mouth of Great Valley Creek, the altitude of the terrace top is 1420 to 1440 feet. It is composed of calcareous gravel, leached to a depth of 15 to 20 feet and somewhat cemented in certain layers. At Shango the level is also 1420–1440 feet; at Red House 1460–1480 feet. At this latter place leaching was observed to a depth of 15 feet. Two miles farther southwest the level is 1460–1480 feet.

A small piece of terrace 1 mile southwest of Quaker Bridge slopes from 1480 feet at the north end to 1400 feet at the south, with stream-cut scarps between, showing that the southern part is a surface of fluvial degradation. A cut at the north end shows 10 feet of tough, dense, weathered material on weathered silt, sand, and gravel. A pit at the south end shows lime-cemented gravel 10 feet below the top of

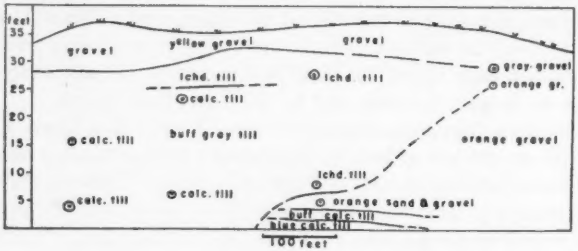

FIGURE 2.—*Diagram of the West Salamanca road cut*

the pit, which top itself is 10–15 feet below the general level of the terrace. Road cuts on the flattish terrace top expose weathered sand and gravel to a depth of 4 feet. The extensive weathering shows that the deposit is older than Wisconsin and hence probably Illinoian.

At Onoville a nose of drift stands at 1480 feet. Shallow road cuts expose weathered drift, but no cuts seen are deep enough to show the depth of weathering. At the Pennsylvania State line there is a 1400-foot terrace on the east side of Allegheny River. There is no evidence that these terrace remnants are of differing ages. They are therefore placed together as outwash of Illinoian age.

ILLINOIAN GRAVEL OVERRIDDEN BY OLEAN ICE

The looped moraine of Olean drift at Peth, in Great Valley, overlies a deposit of gravel whose lithology is similar to that of the Illinoian and unlike that of the rest of the Olean drift. The exposure half a mile west of Peth shows 9½ feet of buff till, leached 8 feet, on 25 feet of coarse calcareous gravel (Table 1). Exposures in the southwestern part of the moraine show only Olean drift. The composition of the moraine seems best interpreted as produced by Olean ice overriding a patch of Illinoian gravel and in that way acquiring locally more limestone and igneous material than is normal to the Olean drift sheet. At Sugartown, 4 miles northeast of Peth, is also a patch of overridden Illinoian drift.

At Allegany a gravel terrace 2 miles long and 1 mile wide rises from 1480 feet above sea level at the west to 1520 feet at the east, with gentle constructional morainic topography, particularly at the northwest end. Its southern side has been trimmed by erosion of the Allegheny River. Two big gravel pits in the western part of this terrace expose gravel containing considerable limestone (Table 1), with many ledges of cemented gravel. Twelve feet of silty leached till (silttil) cap the deposit.

A new excavation for the foundation of a house 1 mile east of Allegany shows 3½

feet of silty till on 6 inches of what seems to be the very much weathered and sticky upper part of the gravel deposit which forms the mass of the terrace. A well being dug 1 mile north-northeast of Allegany shows 4 feet of yellowish silty leached till on 4 feet of dark weathered sand. Many fresh igneous stones near the surface in the till attest to its Wisconsin age. The interpretation of this terrace is that Illinoian gravel

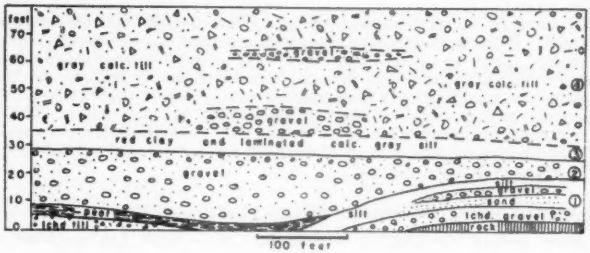

FIGURE 3.—*Diagram of the Otto exposure*

(1) Illinoian; till and coarse leached gravel with many igneous stones, cobbles, and boulders; much-weathered silt at top. (2) Olean; gravel containing few limestone and few igneous pebbles. (3) Binghamton frontal lake. (4) Binghamton; fresh gray drift with many limestone and igneous pebbles.

was overridden by Olean ice leaving a veneer of Olean drift on the surface of Illinoian gravel.

SANGAMON (?) INTERGLACIAL DEPOSIT

In the southern outskirts of the village of Otto, 2 miles northeast of Cattaraugus, Cattaraugus quadrangle, the stream has undercut its east bank to expose a 70- to 80-foot bluff of drift (Pl. 2, fig. 1). At stream level in the middle part of the exposure is a 3–4 foot layer of dense compact brown peat and peaty silt. Its base lies below stream level. Both southward and northward the base of the peat rises above stream level where it can be studied (Fig. 3). Northward from the middle of the exposure the peat lies on weathered blue-gray till, rich in igneous stones, whereas southward a subpeat weathered silt lies on weathered glacial gravel. This gravel contains no limestone but does have an abundance of erratic igneous stones many of which are boulders up to 2 to 2½ feet in diameter. The coarseness, the poor sorting, and the inclined bedding of this gravel suggest that it is kame gravel. The abundance of igneous material distinguishes it from the next overlying gravel which is very low in igneous content. This latter gravel, which overlies both the above-mentioned weathered gravel and also the peat in the middle and northern part of the exposure, is medium coarse, horizontally stratified outwash gravel composed dominantly of the plateau bedrock sandstones and siltstones with very rare limestone or igneous pebbles. It is typical of the Olean drift.

Lying on the Olean gravel is 10–15 feet of laminated, and, in places, varved gray silt and clay, highly calcareous. In the northern part of the exposure this layer also contains 5–8 feet of smooth slick red calcareous clay. The whole layer is evidently a lacustrine deposit formed in an ice-dammed lake.

Above the lacustrine layer is 50 to 60 feet of blue-gray calcareous till with several layers of gravel particularly in its lower part. This drift contains many limestone pebbles as well as many igneous ones and is confidently referred to the Binghamton drift.

Samples of the peat were submitted to Dr. Paul B. Sears, of Oberlin College, for pollen analysis. He permits us to quote from his report:

"All specimens contained a great predominance of coniferous pollen with only suggestions of any deciduous material. With the exception of two specimens which seem to contain only fir and pine, the rest contained fir, spruce and pine. There were some interesting variations in the nature of the peat, some being mainly silt, some wood, some moss, and some mainly sphagnum. In the absence of any information as to stratigraphy of these samples, however, there would be no point in drawing conclusions from this or from certain fluctuations in the proportions of pollen. The indication is clear that the interglacial represented agrees in character with the early postglacial conditions throughout the North Central States when the climate had not warmed sufficiently to permit the dominance of conifers by deciduous forms."

It is concluded because the lowest till and gravel contain abundant igneous material and were deeply weathered, which may well have taken place before the deposition of the peat, that the till and gravel below the peat and silt is of Illinoian age and that the peat and silt is of Sangamon interglacial age.

The succession of events recorded in the exposure is: (1) deposition of till and kame gravel during the Illinoian, (2) weathering during Sangamon interglacial time, (3) accumulation of peat and muck in a low place during the cool humid last phase of the Sangamon, (4) burial by outwash of Olean (Wisconsin) glaciation, (5) waning of Olean ice, (6) approach of Binghamton ice with ponding of a lake in which the highly calcareous lacustrine silts with varves were deposited, (7) further advance and overriding the site by Binghamton (Wisconsin) ice and the deposition of outwash and till.

WISCONSIN GLACIATION

TWO DRIFT SHEETS AT THE WISCONSIN BORDER

The outermost Wisconsin drift on the west side of the Salamanca re-entrant contains normally 12–20 per cent limestone and many igneous erratics, whereas that on the east side is strikingly low in these two constituents. The obvious inference is that ice from two different directions and carrying different material deposited the two types of drift. If these two ice movements were contemporaneous and part of a single glacial episode the types of drift should merge and become indistinguishable at the apex of the re-entrant. Irregularities in lithology are found near the apex, but these seem best explained, as will be discussed later, in ways other than by the merging of two ice movements. If, however, the ice advances on the two sides were not contemporaneous one type of drift should overlie the other. This latter situation is seen in the exposure at Otto where the drift typical of the east side of the re-entrant, designated Olean drift, is overlain by drift typical of that on the western side. In this place also the two drifts are separated by lacustrine silts and varves showing that this locality was free of ice between the two episodes. If the evidence of this exposure be accepted and the ice invasion on the western side is younger than that on the eastern side, the former drift sheet should be traceable eastward from the apex of the re-entrant. If there were a well-marked terminal moraine showing a long ice stand

at such a position, the problem would be simple and would doubtless have been solved long ago. However, no such moraine is present. The problem, therefore, must be attacked by using other criteria. In the present study the lithology of the drifts is used in the attempt to solve the problem. Although there are expectable differences in lithology within a single drift sheet, under the special conditions existing within the area here under study the data seem to be more compatible with the hypothesis of two drift sheets rather than variations within a single one.

It is therefore postulated that the younger drift sheet which forms the western side of the re-entrant can be traced eastward past Elmira, Binghamton, and Oneonta. The name Binghamton for this drift was chosen because it is well displayed at and near this city. The identification of this as a drift sheet separate from the Olean, as previously said, is based on lithologic differences; the Binghamton contains normally 12–20 per cent limestone and 5–7 per cent igneous, whereas the Olean has only 2-3 per cent limestone and a mere smattering of igneous. The question naturally arises as to whether the Olean is not simply the outermost part of a single drift sheet containing fewer erratic stones than the part of the same drift sheet back nearer the outcrops from which the stones were derived. There seems little unanimity of opinion among glacialists on whether or not there should be more concentration of erratics at the margin of a drift sheet or farther back. However, in either case change of lithology should be gradual. In the case here under consideration progressive change in lithology has not been found; the change from one type of drift to the other is sharp and abrupt. The Olean drift has the same lithology from its margin northward to a sharp line of demarcation at which line the limestone and igneous content of the drift suddenly increases. The contrast is so sharp that in the field even the first glance at a good exposure reveals the difference. Northward from this line likewise the new lithology remains constant as far as the Valley Heads moraine. In an east-west direction each drift sheet shows a remarkable uniformity of lithology. If there are any lithologic variations related to either through valleys or transverse valleys influencing the ice flow they have not yet been found. The directions of ice movement as shown near Elmira (Williams, Tarr, and Kindle, 1909) are not incompatible with the hypothesis of a Binghamton drift sheet.

OLEAN DRIFT

Lithology.—The Olean drift is composed dominantly of the sandstones, siltstones, and shales from the bedrock constituting the plateau. Some of these have a small percentage of calcium carbonate in them either disseminated so that it gives a very feeble effervescence with hydrochloric acid, or as calcareous fossils embedded in noncalcareous rock. The lime content of these rocks has been of the utmost importance to the present glacial study, for it has enabled us to be sure our samples were taken in unleached drift and that, therefore, our determination of the limestone content of the drift was trustworthy.

The normal Olean drift contains about 2 per cent of small rounded pebbles of dark blue-gray, very fine-grained, dense limestone (Table 1). Coarse-grained or dolomitic specimens were also found. The content of igneous stones is likewise very low. Sample hand specimens were taken of all the different kinds of igneous rocks

that could be found in each of the eight following places: from Illinoian drift at Steamburg; from Olean drift 1 mile west of Peth, 3 miles south of Cuba, and 3 miles southeast of Rossburg; from Binghamton drift 3 miles southeast of Randolph, 1 mile west of Orlando, 1 mile south of Dalton, 1 mile northwest of Burns (Hornell quadrangle). A. F. Buddington examined these and found that the vast majority of them are typical of the Grenville province and could have come from Quebec or the central Adirondacks. However, in the samples of Olean drift taken 3 miles south of Cuba and that taken 3 miles southeast of Rossburg were porphyries which occur in the Champlain Valley on the east side of the Adirondacks. In the moraine west of Peth was an epidote amygduloid of the type which outcrops, likewise, in the Champlain Valley. These relatively unique rock types suggest ice movement from east of the Adirondacks at the Olean stage.

The Olean drift, however, is at several places abnormally rich in limestone and igneous material. This local enrichment is accounted for as follows. Drift of Illinoian age high in limestones and igneous rocks was deposited in the region. This drift was largely removed by erosion during Sangamon time leaving only patches here and there. When the Olean ice overrode these patches it locally incorporated enough of the older material to produce enrichment in limestones and igneous stones. A notable example of drift of this type is the moraine at Peth. (*See* Table 1.)

Drift border.—The drift border (Pl. 1) is intimately related to the bedrock topography, for, at the edge of the ice sheet, tongues of ice projected in the valleys. At the ends of these ice tongues looped moraines of till and kame gravel were commonly formed. Drift on the uplands is so thin that morainal topography there is seldom present. Since the uplands are covered with dense forest, it was not possible in the limited time available to trace in detail the drift border across the uplands between valleys. This shortcoming in the mapping is not considered serious, however, because accurately located positions of the moraine in the valleys restricts the position which the ice could have occupied over the intervening uplands.

The Olean drift border emerges from beneath the Binghamton drift at "The Narrows" 3 miles southwest of Little Valley. Erratic boulders and till on the north side and top of the hill at the head of Bucktooth Run show its extension eastward and then southward into Little Valley where it forms a moraine in Little Valley Creek. The border thence passes northward over a hill, the crest of which is about 2200 feet in altitude, but it was not actually traced over the upland. It forms a lobate morainal loop at 1540 feet altitude in the next valley eastward. Drift was found at the fire lookout tower at an elevation of about 2300 feet on the hill 2 miles southwest of Ellicottville. Thence, the border follows down the small tributary and forms the looped moraine at Peth. It lies against the south wall of Wright's Creek Valley, gradually rising eastward. It crosses Chapin Hill at 2250 feet and thence descends the west side of Fivemile Creek to the Allegheny Valley. The glacier crossed the Allegheny Valley and deposited drift against the south valley wall through a distance of about 7 miles—*i.e.*, from 1 mile east of Vandalia to 1 mile east of Westons Mills. Thence the border swings northward over the interfluves and southward in the valleys to make looped moraines at Portville and Ceres. The drift border reaches the Pennsylvania State line at South Bolivar, beyond which it was not traced in the present study.

Topography.—The Olean is a thin and topographically relatively unimportant drift sheet. It may well be described as an insignificant coating of till over the uplands with looped moraines in the valleys at the drift border and kame terraces against the lower parts of the valley sides north of the border. The looped moraines are those in Little Valley, at Peth, Portville, and Ceres; that at Peth is the largest. Kame terraces occur here and there along most of the larger valleys; Wrights Creek, Forks Creek, Fivemile Creek, Olean Creek, Haskell Creek, Dodge Creek, Little Genesee Creek, Honeoye Creek, Van Campen Creek, and Genesee River all contain them. The gravel in these kame terraces has the typical low-lime, low-igneous lithology of the Olean drift.

In demonstrating that Olean ice pushed across the Allegheny Valley in the neighborhood of Olean, several bits of glacial topography have special interest. A large kame 1 mile east of Westons Mills stands out in the valley and rises 100 feet above the valley floor. A big gravel pit in the eastern part of this kame exposes medium coarse gravel dipping eastward. This kame marks the eastern edge of the ice lobe that invaded the Allegheny Valley. There are two small isolated kames on the south side of the Allegheny River between Westons Mills and Olean. On the south side of the river at Olean is a single large isolated kame, now occupied by the city cemetery. Olean itself is built on a gently rolling kamelike mass of low-lime drift. One mile west of Allegany a similar low mound of coarse gravelly drift half a mile wide and 1 mile long lies out in the main valley. Its crest is 1480 feet in elevation.

Two miles west of Allegany a deposit of drift marks the western edge of the ice lobe in the Allegheny Valley and is interpreted as a crevasse filling made by the waters of the diverted Allegheny River. For this reason it is described in some detail. It is a large mass of sand and gravel forming a blunt terrace or nose against the south valley wall at the mouth of Birch Run. Its base is at 1480 feet, the level of the valley floor here, and its crest is at 1680 feet. This terrace has an elevated central core with subsidiary noselike ridges projecting at slightly lower elevations. The Hornell Gravel Company's pit occupies the north end of the central of the three noses. The exposed face of the pit is 120 feet high. Three suites of deposits are seen: (1) At the top is deltaic gravel, 8 feet of topset beds on 17 feet of westward-dipping foresets. (2) The middle suite is sand and silt interbedded and dipping gently westward. Occasionally thin layers or lenses of gravel are seen. The strata are faulted as by settling. In one place in the west end of the pit the layers are folded into a vertical-limbed monocline 10 feet high. One mass, 30 feet high, 40 feet long, and 20 feet wide is composed of remarkably even-sized pebbles about an inch in diameter with the interstices filled with silt. The exposed surfaces of the mass stand vertically like a bank of loess. A gravel-bearing current of water seems to have become choked with silt and been forced to deposit its load abruptly. (3) The lowest suite, 30–40 feet thick, is composed of coarse bouldery gravel. The deposit is calcareous below 10–12 feet of leached gravel. The lithology is normal to the Olean drift.

BINGHAMTON DRIFT

Lithology.—The Binghamton drift differs strikingly from the Olean drift in having an abundance of both igneous erratics and of limestones (Table 1). The former range from 5 to 7 per cent, and the latter from 12 to 25 per cent. These two constitu-

ents, however, being more conspicuous than the drab gray and browns of the local plateau bedrock, make the Binghamton drift look quite different from the Olean drift. It might be described as looking "brighter" and "more striking." (Pl. 2, fig. 3.) The igneous erratics are all of types common to the Grenville province of Ontario and the western Adirondacks. The limestones are characteristically rounded, dark bluish gray, and very fine-grained. However, a few are light gray, and some are coarse -grained.

There are two variations from the normal lithology. Where the Binghamton ice overrode Olean drift it seems to have picked up so much Olean material that the normal Binghamton drift locally and near its margin is diluted with enough plateau rock material to give a pebble count intermediate between the normal for either of the two drift sheets (Table 1). Also, where a tongue of Binghamton ice projected into one of the deep valleys, local plateau stones or Olean stones may have been washed down into the ice-marginal deposits to dilute them below their normal limestone and igneous content.

The second modification is a local enrichment of igneous material and dilution of the limestone content of the drift. This appears to have taken place through overriding and incorporating some of the leached Illinoian drift. The fact that a considerable proportion of the igneous stones in this type of drift are partly weathered strengthens this interpretation. Such drift occurs at Orlando, Ellicottville quadrangle, and in the large moraine 3 miles east of Randolph.

Drift border.—The Binghamton drift border (Fig. 1) passes from Ohio into Pennsylvania 16 miles southwest of Newcastle.[1] The border across northwestern Pennsylvania has been mapped in detail by Leverett (1934) and was only reviewed in the present study.

The border enters New York from Pennsylvania on the east side of Conewango Valley, 3½ miles east of Fentonville and 9 miles southeast of Jamestown. It trends northward as a mile-wide belt of terminal moraine along the valley wall rising to 2000 feet in altitude at several places. It turns eastward to form the large and striking moraine across the capacious preglacial valley north of Steamburg (Pl. 1). Thence it passes northward, still as a strong morainic belt, with lobes into the valleys. The border then turns eastward, projecting to make strong morainal patches in the north branch of Little Valley Creek and in Toad Hollow. It forms morainal loops in the valleys at Orlando, Ellicottville quadrangle, and in Hinman Valley. Thence it is traced eastward past Plato to the kames 1½ miles north of Ashford. It crosses Devereaux Branch 3 miles northeast of Ashford. It then trends southeast to Ischua, Olean quadrangle, where a lobe of ice pushed southward down Ischua Creek valley and deposited the strong moraine 2 miles south of the village. From Ischua the border was traced eastward to the north shore of Cuba Lake. At Abbot are good Binghamton drift kames. From the east end of the lake the border follows the south side of Black Creek valley, Angelica quadrangle, to the Genesee Valley, up which it projects to Belvidere. Thence the border bears northward along the east side of Genesee Valley. It projects eastward into the tributary valleys. In Baker Creek are large Binghamton drift kames 1½ miles northwest of Angelica. In

[1] The 8-mile wide fringe of drift to the south is here interpreted as Illinoian.

Wigwam Creek are two conspicuous kames of this drift 3 miles east-northeast of Belfast. The drift border leaves the Angelica quadrangle in its northeast corner at an altitude of 1500 feet.

The Binghamton border from here east was not traced continuously but was located by a succession of north-south traverses to find the outermost deposit of the Binghamton type of drift. These are plotted on Figure 1 and connected by a dotted line. It is believed that this technique has located the drift border, to within a mile or two, eastward to and beyond Oneonta.

Where the border leaves the Genesee Valley in the southwest corner of the Nunda quadrangle it passes eastward at 1800 feet around the north side of the highland. It projects as a nose into the valley 2 miles south of Dalton producing morainal topography to an elevation of 1800 feet. The Valley Heads moraine here lies only 2 miles north of Dalton with its crest at 1400 feet, bringing the two moraines into close proximity at this place. The Binghamton border thence goes eastward past Bakertown and Westview and then southward along the west side of Canisteo and Canacadea valleys to Alfred Station. Within this north-south stretch there is a great development of Binghamton moraine and of kame terraces (Pl. 2, fig. 2).

The border passes eastward south of Hartsville to 1½ miles south of South Canisteo where 80 feet of typical fresh Binghamton till lies on 20 feet of Binghamton gravel. Thence the border trends north crossing the Canisteo River several miles east of Adrian. It lies just south of Risingville, Thurston, and Campbell and just north of Painted Post and Corning.

In Caton Creek, 3 miles south of Corning, 30 feet of Binghamton outwash gravel lies on the eroded surface of Olean till. Many good-sized, slightly waterworn blocks of rock at the contact of the two drifts suggest a concentration of the coarse material during 20 or 30 feet of erosion of the top of the Olean drift before the upper gravel was laid down. At the village of Caton only Olean drift is found. A big highway cut through a mass of drift 5 miles west of Elmira exposes 40 feet of Binghamton till on 20 feet of Binghamton gravel, but a mile south of here a big exposure on the north side of Hendy Creek 1 mile from its mouth shows Olean till.

The drift border turns south at Elmira along Seely Creek Valley with kame terraces of Binghamton drift at Webbs Mills and till at Daggett, Middletown, and Athens south of the Pennsylvania State line. The border from Athens follows up the Susquehanna Valley making the conspicuous moraine on the south side of the river from Owego to and including Binghamton, from which the name for this drift sheet has been selected. Splendid big exposures are seen along the highway which, at the time of the visit, was being widened and improved. One such cut is just west of Owego, and another, 80 feet high, between Tioga Center and Smithboro.

From Binghamton the drift border follows up the Chenango Valley almost to Oxford. A gravel pit 3½ miles southwest of Oxford contains 35 per cent of limestone. From Oxford the border trends eastward to Unadilla River in the valley of which it projected to Rockdale. Thence it follows eastward again and into the valley of the Susquehanna where a lobe projected southwestward to Sidney. From Sidney downstream to Binghamton the Susquehanna Valley contains Olean drift, but from Sidney upstream it contains the Binghamton drift. The ice edge seemed to have crossed the valley and impinged on the south valley wall, for on the south side of the valley at Sidney, at Unadilla, and at Oneonta (250 feet above river level) is found Binghamton drift. The ice did not pass farther south at this stage, however, for Olean drift is found in Carrs Creek, Outlet Creek, and Charlotte Creek. An exposure, 40 feet high, of Olean gravel is seen 1 mile west of Davenport in the creek valley. At Cooperstown Junction the drift border leaves the Susquehanna Valley and follows up that of Schenevus Creek. At the headwaters divide of this latter creek, 3½ miles west of Richmondville, the Binghamton drift, seen in a large road cut, contains 15 per cent limestone and an appreciable amount of igneous rocks.

From here eastward the lithologic distinction between Binghamton and Olean drift becomes uncertain. Further investigation lies beyond the scope of the present study.

Topography.—The Binghamton drift sheet exhibits a considerable variety of topographic forms which may, for simplicity, be grouped into six types: (1) terminal

moraine, (2) ground moraine, (3) drumlin, (4) kame terrace, (5) "valley stopper" moraine, (6) "valley choker" moraine.

(1) The terminal moraine is a belt of thickened drift about a mile wide within which drift controls the topography. Kames are common, and undrained depressions numerous. It is mappable from the Ohio State line northeastward across western Pennsylvania and western New York as far as Little Valley in the Cattarau-

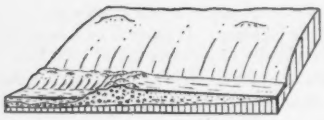

FIGURE 4.—*Diagram of "valley stopper" moraine*

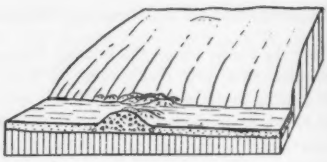

FIGURE 5.—*Diagram of "valley choker" moraine*

gus, New York, quadrangle. A belt of terminal moraine of this drift sheet is also found in the Susquehanna Valley between Owego and Binghamton.

(2) Ground moraine blankets the interfluve uplands of the region covered by this drift sheet. It consists predominantly of till, though a few small kames and kame fields have been noted.

(3) Drumlins dominate the topography of the ground moraine in a considerable area in western New York and northwestern Pennsylvania, notably in the Clymer and Northeast quadrangles. They are 50–80 feet high and between half a mile and a mile long. Their axes show that the direction of ice motion was south-southeast at the time of their formation. Most of them are remarkably smooth on top and sides showing absence of ice-marginal accumulation on their streamlined surfaces.

(4) Kame terraces are banked against the lower slopes of most of the major valleys. They are dominantly composed of fairly coarse kame gravel, but a considerable amount of deltaic gravel and plain gravel of smaller size and better sorting is also present. The valleyward slopes of many of the kame terraces show ice-contact topography.

(5) "Valley stopper" moraine. Within the plateau region many valley bottoms sloped northward. When an ice tongue lay in such a valley north of the bedrock divide, for a considerable time, marginal and frontal accumulation of a till and kame moraine took place, and a noteworthy valley train was formed, the top of which sloped southward from the morainal area to, and in some cases across, the earlier divide (Fig. 4). Numerous examples are seen of streams that head at the morainic area and flow southward on the outwash plains across the old divides. An exposure in such outwash near the head of Hinman Valley, Ellicottville quadrangle, shows 12 feet of medium coarse gravel on 100 feet of buff to blue-gray silt. Where the valley train is pitted by the melting of buried ice blocks it is assumed that the ice stand, at the kane area, was recessional from an earlier farther advance, but where the valley train is not pitted the ice stand, from which the outwash emanated, is interpreted as a readvance.

Northward from each "valley stopper" moraine there is characteristically a low

FIGURE 1.—OTTO EXPOSURE
Binghamton till at top of cut lies on Olean gravel in middle of picture. Peat forms dark ledge at stream level.

FIGURE 2.—BINGHAMTON KAMES
Almond, Hornell quadrangle.

FIGURE 3.—BINGHAMTON DRIFT
3 miles west of Elmira.

part of the valley fringed by kame terraces banked against the valley sides and graded to the valley train. The central depression not uncommonly is floored by lake clays.

Twenty-three "valley stopper" moraines were studied and mapped at the following places (crescentic symbols, Fig. 1); two miles south of Sugar Grove (Youngsville quadrangle); Godard (Erie quadrangle); Lake Pleasant (Northeast quadrangle); Watts Flats (Chautauqua quadrangle); 2 miles north of Sherman, 2 miles west of Sherman, at North Clymer, 2½ miles north of Clymer, and 1½ miles west of Clymer (Clymer quadrangle); Northeast corner (Neshonnock quadrangle); Kashner (Shenango quadrangle); Harmonsburg (Linesville quadrangle); Blooming Valley (Meadville quadrangle); Townville (Townville quadrangle); McLane and Baddad (Cambridge Springs quadrangle); 3 miles southeast of Wattsburg (Union City quadrangle); West Valley, 2 miles west of Machias, Hinman Valley (Ellicottville quadrangle); Rawson, Farmersville, 2 miles west of Freedom (Franklinville quadrangle); 4 miles south of Cattaraugus (Cattaraugus quadrangle).

(6) "Valley choker" moraine. A moraine lies athwart, and partly chokes, the southward-sloping valley at Waterford, Union City quadrangle (Fig. 5). The moraine is composed dominantly of kame gravel, but there is also till present. The drainage traverses the morainal areas, and the valley train above is graded to that below the morainic constriction.

At Jamestown also a "valley choker" moraine crosses the valley of Chadakoin Creek, a tributary to Conewango Creek. The drainage conditions at this locality, while started in Binghamton time, seem to have been modified during the Valley Heads glaciation.

Explanation of topography.—The more or less continuous terminal moraine belt, in the western part of the area, and absence of recessional moraines to the north, coupled with the presence of drumlins, kame terraces, valley stopper moraines, and valley choker moraines, seem best explained on the hypothesis of an active ice edge which fluctuated near its maximum stand long enough to deposit the belt of terminal moraine. Then followed diminution of supply which resulted in thinning and local stagnation of the peripheral zone of the ice sheet. The remarkably smooth and streamlined surfaces of the drumlins that occupy the uplands suggest that they were made by some type of laminar-flow mechanics within the glacier and that liberation from the ice took place in such fashion that no ice-marginal material was deposited on top of them. If the edge of active but waning ice had receded across them, rougher topography should have been produced by liberation of debris at this edge. It seems, therefore, a tenable hypothesis that the drumlins were made under the ice while it was thick enough to produce laminar flow and that the enclosing ice stagnated and melted from around them without spoiling the smoothness of their surfaces. The meltwater must have drained off quietly and slowly to lower channels so that kame terraces were not built against the drumlin sides. Along the sides and ends of residual ice masses lower down in the main valley, however, kame terraces and "valley stopper" moraines were formed.

VALLEY HEADS MORAINE

Description.—The inner, or north, edge of the Binghamton drift is covered by the Valley Heads drift which marks the northern limit of the present study. This

moraine, like the older ones, reflects the effect of the dissected plateau surface on the ice flow. The Valley Heads moraine is the most conspicuous accumulation of drift in New York State, and both its topographic and drainage influence are well displayed. The principal morainic masses are in the deep valleys of the plateau, with valley trains extending southward from them. Streams generally flow southward, over the outwash, and northward from the moraine which therefore constitutes a divide. Most of the valley segments of this moraine then are "valley stoppers" as above described.

Location.—The Valley Heads moraine enters New York State from the west as the continuation of the Lake Escarpment morainic system of Leverett (1902). It appears as a morainic belt 1 to 3 miles wide extending east-northeast for some 50 miles. At the western State line and over a considerable part of this distance the moraine is a single belt which may include locally two or more minor ridges. At the valley crossings, especially where the valleys are deep, a separate ridge is found south or outside of the main morainic accumulation. Leverett (1902) has described such in the Chautauqua Lake Valley and Cassadaga Valley. Between these valleys and eastward for a distance of some 5 miles the outer moraine, which is small, is distinctly separate. Bear Lake and the lakes near Cassadaga (Dunkirk quadrangle) lie between the two parts of this moraine.

Eastward from the junction of the two branches of the moraine at Arkwright a belt of moraine about a mile wide crosses at the headwaters of Conewango Creek and swings down to connect with the great pile of morainic material east of Dayton in Cattaraugus Valley, where some 600 feet of relief consists largely of drift. This blocking has had important influences on the local drainage of the Cattaraugus quadrangle.

Cattaraugus Creek flowing north has cut through an old divide southeast of Gowanda to capture an area which lies south of the main moraine. Only two other streams west of Genesee River, Canadaway and Chautauqua creeks, have any important part of their drainage basins on both sides of the Valley Heads moraine.

The divide area west of Genesee River in western Wyoming County seems to have been the position of contact between ice from the Ontario and from the Erie lake basins. Uneven interlobate morainic topography stretches over a width of half a dozen miles and shows a lack of drift concentration such as is found in the valleys.

East of the interlobate area the ice advanced farther into the plateau with greater lobation in the valleys and built strong moraines in them. The general morainic belt follows a broad arc across west-central New York, with its southern extension reaching to within 20 miles of the southern State boundary in Chemung County. A broad loop across the head of Mohawk valley marks the eastern limits of the moraine south of the Adirondacks. The Ontarian part of the Valley Heads moraine shows the same dual or multiple features as occur in western New York. The outer morainic fringe lies a few miles beyond the major drift pile in most of the valleys. It is marked by morainic ridges, usually small, on the hillsides above the outwash which has aggraded the valleys up to the big moraine. The dual character shows that the ice withdrew slightly from its maximum extent before it built the major moraine.

Additional evidence of the presence of ice south of the present moraine consists of

the kettle lakes and swamps which lie in the head of the outwash in such valleys as that of Mud Creek northeast of Bath, the Tioughnioga valley near Tully, and the valley south of Peterboro. Such features seem to occur principally where the valley being filled was a mile or more in width. Narrower valleys seem not to have held sufficient ice to outlast the deposition of the outwash which therefore filled such depressions as may have been formed.

Over the uplands there was less accumulation of drift, and a probably fluctuating ice front spread the deposits thinly. Therefore the Valley Heads moraine in these places is not so distinctively developed, but its position can usually be determined, though the maximum limits reached by the Valley Heads ice over the uplands remains in doubt in many places.

Lithology.—Valley Heads drift shows variations in composition which accord with its origin. The first flood of Valley Heads ice, coming into most areas, dug up the drift of earlier deposition and incorporated it in its own drift. Thus very little difference in lithology or weathering is to be found between the Binghamton drift and the most advanced parts of the Valley Heads drift. After equilibrium was established, with moraine building at a nearly stationary ice front, the proportion of distant rocks decreased, and that of local rocks increased so as to change materially the composition of the Valley Heads drift. This aspect of the drift will be discussed in another publication.

Outwash.—The surface outwash heading at the Valley Heads moraine and crossing the Binghamton drift area was derived, for the most part, from the later phases of Valley Heads ice work and differs in composition from the earlier drift in most places. Its valley train form and continuous grade up to the moraine, from which it was built, provide the distinguishing features of this outwash.

CORRELATION

PRE-ILLINOIAN

No pre-Illinoian drift was found within the area of the current study, but the fact that Illinoian drift lies in Allegheny Valley and tributary valleys down to present drainage level suggests that the diversion of this major stream from its former course northward had been caused by a preceding ice sheet.

ILLINOIAN

The age is based on the great depth of weathering, the considerable amount of erosion, and the presence of interglacial deposit at Otto. The drift was traced into Pennsylvania where Leverett (1934) considers it to be Illinoian and into Ohio where White (1939) also considers it Illinoian.

WISCONSIN

The exposure at Otto, as well as another 3 miles northeast of Randolph, shows Olean drift separated from overlying Binghamton drift by 15 to 20 feet of calcareous gray lacustrine clays and silts. The Olean drift is evidently older than the Binghamton, but how much older has not been determined. No weathering of the top of the lower drift was detected. This is not surprising in view of the fact that intra-Wis-

consin weathering would probably be slight and would be found only by great good luck and under the most favorable conditions. However, the stratigraphic relationships in the exposures as well as the geographic distribution of the drift sheets and their different lithologies show that the territory was largely deglaciated after Olean time and that the center of dispersal shifted westward so that the Binghamton ice advanced into the region from a more northerly direction. This notable withdrawal, rearrangement, and readvance of ice lobes is sufficient evidence to constitute an important demarcation within the Wisconsin. At several places in and near the area, Olean drift and outwash seem to have been trenched 20± feet before Binghamton outwash was deposited (as 2 miles west of Allegany and a mile north of Salamanca), and in turn the Binghamton drift and outwash were trenched before Valley Heads outwash was deposited (terraces of the Susquehanna). But this study of outwash relationships, fruitful as it probably would be, has not been carried far enough to yield definite results. Within the area covered by Olean drift large alluvial fans are common, showing considerable post-drift erosion of the plateau slopes. Since such fans are not found under similar topographic conditions in Binghamton drift territory it is inferred that Olean glaciation was perceptibly older than Binghamton.

There was evidently a significant retreat of Binghamton ice, a considerable lapse of time, and a notable rearrangement of ice lobes before the advance of the Valley Heads ice. The lithology of the two drifts is sufficiently different to show a somewhat different path of ice movement. The striae in Central New York trend in a somewhat different direction, and at Cyler, New York, there is leached and slightly weathered material between Binghamton and Valley Heads drift. This evidence seems to warrant making a separate stadium of the Valley Heads episodes.

Correlation of the drift sheets of the Salamanca area with those of the Mississippi Valley region may be unduly hazardous and possibly premature. However, some deductions may be drawn which might serve as the beginning of such correlation. The classic works of Leverett and Taylor on the history of the Great Lakes furnishes a most important yardstick. It has been demonstrated that the whole episode of Lake Arkona intervened between the Valley Heads glaciation and the Hamberg and Marilla moraines of western New York. Likewise, by their relation to Lake Arkona, the Hamberg and Marilla moraines are correlated with the Paris-Galt moraines on Ontario, and this in turn with the Port Huron moraine of Ontario and Michigan which latter becomes the Mankato moraine of Wisconsin and Minnesota. Leighton (1933) divides the Wisconsin into four stadia (oldest to youngest): Iowan, Tazewell, Cary, Mankato. In similar fashion by its relation to Lake Maumee the Valley Heads is correlated with the Lake Escarpment and the Defiance, which is traced across Michigan into the Cary of Illinois.

The correlation of the Binghamton and the Olean drifts is much more uncertain at present. Three different correlations lie within the scope of possible hypothesis:

Hypothesis I		*Hypothesis II*		*Hypothesis III*	
Hamberg and Marilla	= Mankato	Hamberg and Marilla	= Mankato	Hamberg and Marilla	= Mankato
Valley Heads	= Cary	Valley Heads	= Cary	Valley Heads	= Cary
Binghamton	= Tazewell	Binghamton	= Tazewell	Binghamton	= Cary
Olean	= Iowan	Olean	= Tazewell	Olean	= Tazewell

Under Hypothesis I the Binghamton correlates with the Tazewell. The latter is represented in the middle west by a series of large and important moraines. On the west side of the Salamanca re-entrant and westward into Ohio the magnitude of the Binghamton is not incompatible with the mid-west occurrences. However, east of the re-entrant the feeble moraines, suggesting a short glaciation, are out of harmony with those to the west. Yet it may well be that the Binghamton in central New York is only the outermost of a series of Tazewell moraines all others of which have been buried and obscured by the Valley Heads invasion. White (personal communication) thinks that there is, in Ohio, Wisconsin drift older than the probable prolongation of the Binghamton across that State. Also, if the Olean border is the terminal moraine traced across eastern Pennsylvania by Lewis (1884) and is continuous all the way, it becomes the Harbor Hill moraine of Long Island (Fuller, 1914). This leaves the Ronkonkoma moraine as a still older Wisconsin episode. And, since the latter is separated in time from the Harbor Hill by the erosion of the Smithtown Valley, opinion of recent years has considered the Ronkonkoma as possibly Iowan. This would mean that the Olean cannot be Iowan. Considerable work remains to be done in New Jersey, Pennsylvania, and New York to establish the relation between the Olean and the Harbor Hill.

Hypothesis II explains certain facts but encounters difficulty in placing in a single stadium ice movements into the same region from as different directions as occurred in Olean and Binghamton time. Such withdrawal and rearrangement of ice lobes have elsewhere been used to demark stadia.

Hypothesis III would be acceptable for the drifts east of the re-entrant, but it falls into difficulty in central Ohio and Indiana, though this difficulty may disappear when better correlations in these States have been established. In the present state of knowledge the authors favor this third hypothesis.

PLEISTOCENE HISTORY

Illinoian ice invaded western New York from the north and northwest. Since drift of this age is found in valleys down to, and probably below, present river levels, it is believed that the valleys of that time were cut at least as deep as they are today. The Illinoian ice edge extended to Steamburg, to Salamanca, to Windfall Creek, and Woodchuck Hollow, north of Olean. A valley train of Illinoian gravel filled the Allegheny Valley to the present 1480-foot level.

Upon withdrawal of the Illinoian ice, erosion largely stripped away the Illinoian drift, leaving only patches of deeply weathered till, scattered erratics in the mantle rock, and small partly dissected remnants of a valley train standing as terraces in the Allegheny Valley. The accumulation of peat at Otto took place in the latter part of the Sangamon interval after the underlying drift had suffered deep subaerial weathering and when the climate was turning cold and wet from the oncoming Olean ice.

Olean ice, of early Wisconsin age, invaded the area from the east, bringing with it Champlain Valley rocks. Possibly this movement was largely around the south side of the Adirondacks. During the long traverse across the hilly plateau district the ice acquired a large predominance of plateau stones to give the drift its characteristic lithology. Judging from the small amount of drift deposited by this ice invasion,

it must have been of relatively short duration. Both during advance and recession ponding and derangement of drainage was effected. A large but short-lived ponding of the Allegheny took place when an ice tongue crossed the river at Olean and impinged against the south valley wall.

In the next episode Binghamton ice invaded the area. East of the re-entrant it seems to have come from a more northerly direction than its predecessor, whereas on the west side it came from the northwest. This ice brought with it a difficiently different suite of rocks to make its drift distinctive. It overrode the Olean drift completely at the west but fell short of its margin from Little Valley eastward. It dumped outwash into the valleys such as Ischua, Oil Creek, Great Valley, and Olean Valley to make valley trains of Binghamton gravel crossing areas of Olean drift. Southwest of Little Valley the ice remained at its maximum stand long enough to build a stout terminal moraine. East of Little Valley, however, it did not remain at its most advanced position very long but fell back to the line of West Valley, Machias, Sandusky, and Caneadea where recessional features were built.

A relatively short but significant episode of erosion and weathering followed the Binghamton withdrawal prior to the advance of the Valley Heads ice. This ice invasion fell short of the other two but was of long duration for it built gigantic moraines of the "Valley stopper" type in the northward-sloping valleys of the plateau. So large were these moraines that they have formed the divides in the valleys, except the very largest ones such as the Genesee. The ice of this invasion spread east, south, and west out of the Lake Ontario basin and southwestward across the Lake Erie basin, in which latter basin the south edge of the lobe lay along the plateau escarpment. As this lobe waned from the Erie basin successive frontal moraines were produced descending diagonally down the face of the escarpment and disappearing under the lake and lake sediments. Upon withdrawal of the Valley Heads ice the Pleistocene history of the region here under discussion came to a close.

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PROJECT GRANT 367/41

73°00'

9°00'

A

Caledonia Fissure

Sea Level

B

Mercedes Fault Zone

Esperanza Dome

Sea Level

Río de Oro Anticline

K

K'

Sea Level

CONFLUENCIA DOME

Río Dado

Río Lebrija

Río Lebrija or Cocho Ricaurte

Río Tamar

Río de Oro

Playa Necesidad

Airport

Río de Oro

Río Sogamoso

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Río Eustaquio

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Río Opón

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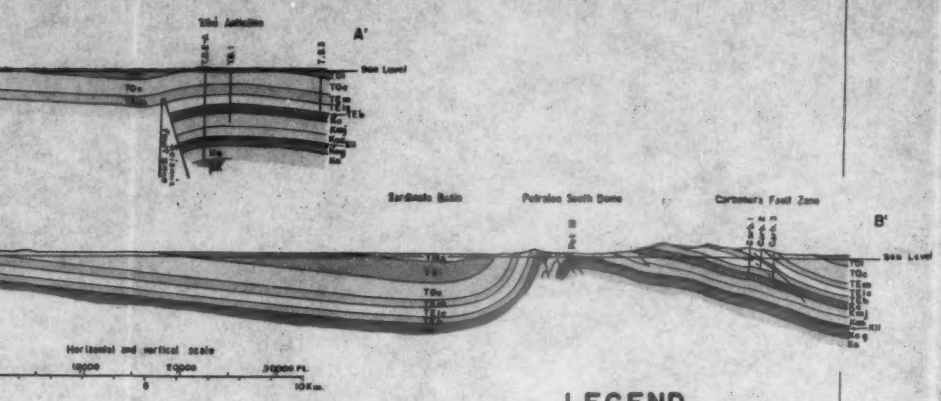

LEGEND

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	TOl	León	
	TOc	Carbonera	
	TEm	Mirador	
	TElc	Los Cuervos	
	TEb	Barco	KTo Orocué
CRETACEOUS	K?	Catatumbo	
	Kcmj	Colón-Mito Juan	Kmj, Mito Juan; Kcs, Colón Shale
	Kc	Cogollo-La Luna	Kll, La Luna; Kcg, Cogollo
	Ku	Uribante	
	pre-Cretaceous		

- Downdropped side of normal fault
- Overthrust side of thrust fault
- International boundary
- Concession boundary
- Selected area boundary
- Automobile road
- Pipe line

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Los Manueles Field

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Uribante River

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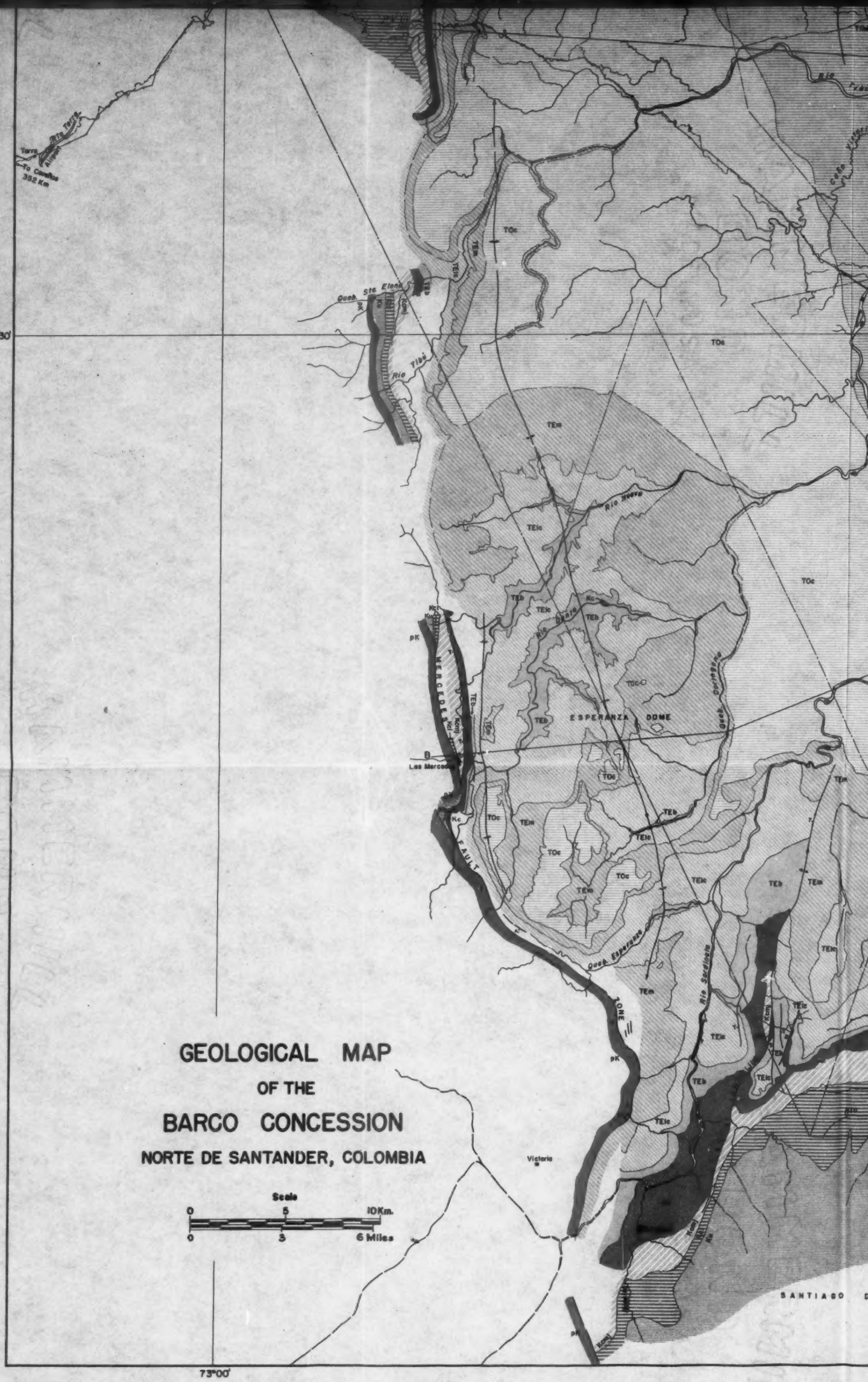
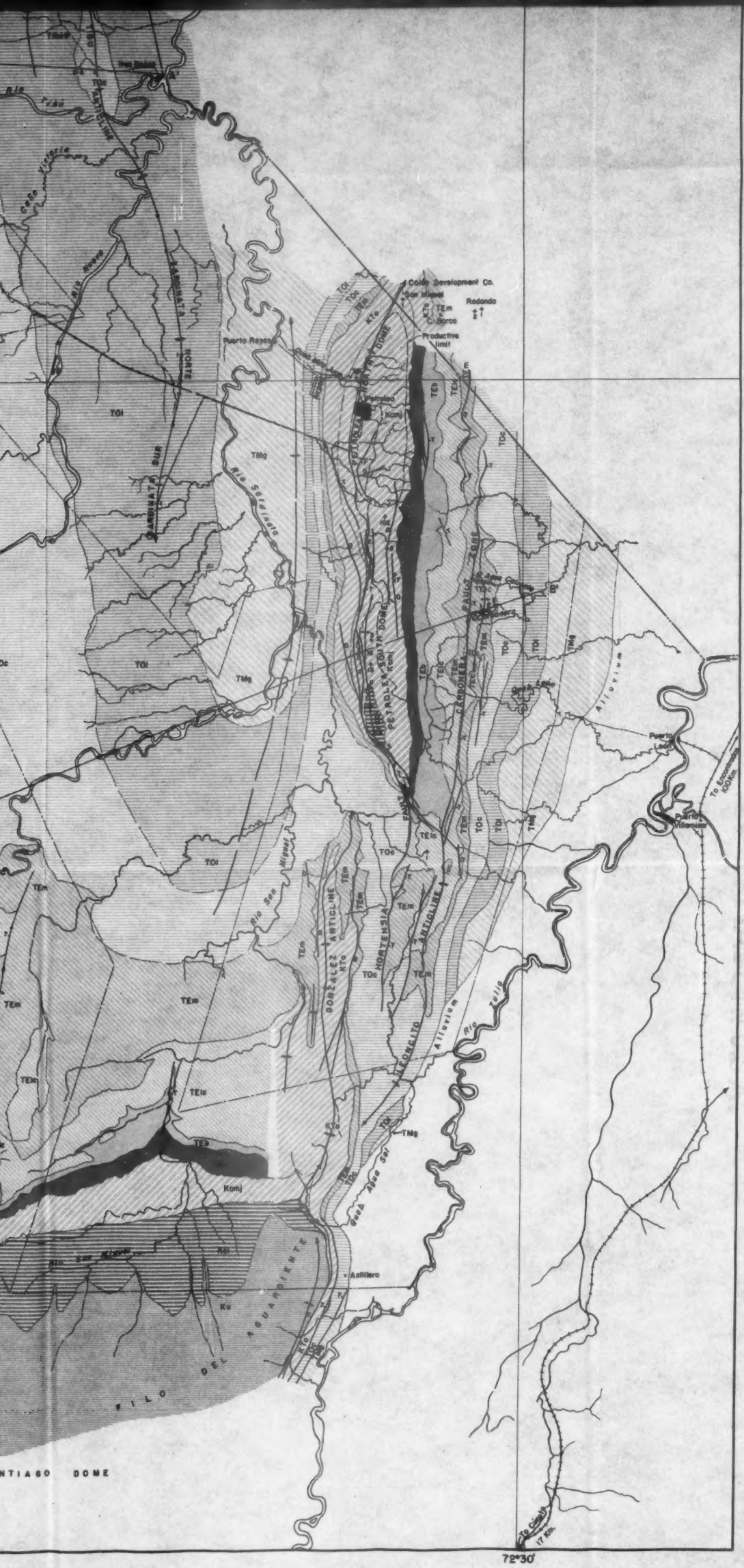


GEOLOGICAL MAP
OF THE
BARCO CONCESSION
NORTE DE SANTANDER, COLOMBIA

GEOLOGICAL MAP AND CROSS SECTIONS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GEOLOGY OF THE BARCO CONCESSION, REPUBLIC OF COLOMBIA, SOUTH AMERICA

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AND JAMES W. BOWLER

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ABSTRACT

The Barco Concession, as granted by the Colombian government in 1931, comprises slightly over 1,000,000 acres lying along the Venezuelan boundary in the upper Río Catatumbo drainage basin. The topography varies from gently rolling to low mountainous. The climate is wet equatorial. The area is nearly all virgin forest.

The sediments involved range in age from Lower Cretaceous to Pliocene-Pleistocene. The Lower Cretaceous rests on a basement of pre-Cretaceous metamorphic and plutonic rocks, is entirely marine, approximately 700 meters thick, and is divided into the Uribante and Cogollo formations. The Upper Cretaceous is dominantly marine but includes some brackish-water deposits in its upper part, is approximately 950 meters thick, and is divided into the La Luna, Colón, Mito Juan, and Catatumbo formations. The last named is here defined for the first time. No unconformity is known to exist between the Cretaceous and Tertiary systems; the change is transitional in this area, and the position of the Cretaceous-Tertiary contact is doubtful.

The Tertiary rocks, characteristically nonmarine but which include a few marine beds, are approximately 2500 meters thick within the Concession. This figure would be increased 75 per cent if the remainder of the Guayabo group as known just southeast of Cúcuta were included. The Tertiary is divided into the Barco, Los Cuervos, Mirador, Carbonera, León formations, the Guayabo group, and the Necesidad formation. Of these Barco, Los Cuervos, Carbonera, León, and Necesidad are new formational names here defined. No major unconformities are known in the Tertiary below the base of the Pliocene (?) Necesidad formation. A minor unconformity occurs at least locally at the base of the Mirador, and there may be another local unconformity at the top of this formation.

Within the Concession oil production has been obtained from the Uribante, Cogollo, La Luna, Mito Juan, Catatumbo, Barco, and Los Cuervos formations.

Numerous oil and gas seepages occur on truncated anticlines. Two dikes of solid hydrocarbon have been found on and near the Concession. Bituminous sandstones of the Catatumbo and Barco formations are common on truncated anticlines.

The Barco Concession lies near the southwestern edge of a northeasterly plunging lobe of the Maracaibo basin between the Sierra de Perijá on the west and the Sierra de Mérida on the southeast. This lobe is more or less bisected by a truncated anticlinorium extending from immediately north of the bifurcation of the Cordillera Oriental northward through the Petrolea anticline and its extension in the Tarra anticline of western Venezuela. The total length of this bisecting anticlinorium is at least 120 kilometers, of which one third is on the Concession. East of this anticlinorium lies the Zulia syncline, and to the west is the Sardinata structural depression. Along the western edge of the upper Maracaibo basin there is a zone of folding and faulting in the eastern foothills of the Sierra de Perijá. About midway between these foothill folds and the bisecting anticlinorium is a north-south trend of uplift called the folds of the Sardinata depression. Major folding took place during late and post-Miocene time, but it began on a minor scale much earlier.

The Petrolea field has six productive zones, all Cretaceous. Zone 3, the most extensive, has a proven area of approximately 1700 hectares (4200 acres). Well depths range from 26 to 513 meters. The field has 124 producing wells and is considered fully developed. The gravity of the oil averages 46° A.P.I. A 12-inch pipe line 421 kilometers (261 miles) long extends from the field to the Gulf of Morosquillo.

The Río de Oro field produces black oil of 32° to 40° A.P.I. gravity from sandstones of the Catatumbo and uppermost Mito Juan formations. The productive area is about 170 hectares (420 acres). It is partially developed with nine wells averaging 430 meters in depth.

The Tres Bocas field, on the Tibú anticline, has had only three tests—two small wells in the Barco formation and one good producer in the Tibú member of the Uribante formation. This field is just past the discovery stage and has not been defined by drilling.

The Socuavó field has had two tests, both commercially productive, one of which produces from the Barco formation, and the other from the Uribante formation. This field, also, is just past the discovery stage and has not been defined by drilling.

The Carbonera field has been developed by three small wells pumping black oil of 21° A.P.I. gravity.

INTRODUCTION

The Barco Concession acquired its name from General Virgilio Barco, to whom a concession for petroleum exploitation in the upper Catatumbo basin was granted by the Colombian government in 1905. He built a mule trail to the Petrolea valley and erected a small still for refining seepage oil. After sundry vicissitudes the concession was canceled by the Colombian government in 1926. A new concession covering a large part of the original area was granted to the Colombian Petroleum Company under the terms of the Chaux-Folsom contract dated March 3, 1931, which contract was approved by the Colombian congress in Law 80 of 1931. This opened the period of systematic exploration. The name of the pioneer is still customarily applied to the Concession, as is fitting.

The Concession lies along the Colombian-Venezuelan boundary between latitudes 8° 8′ N. and approximately 9° 12′ N. and is crossed in its western portion by the 73rd Meridian west of Greenwich (Fig. 1). The Concession as granted covered an area of approximately 414,000 hectares, or approximately 1,022,000 acres. From this the operating company has selected 186,805 hectares, or approximately 460,000 acres, for exploitation, while the remainder has reverted to the free disposition of the Nation in accordance with the law. The exploitation period is 40 years from August 25, 1941.

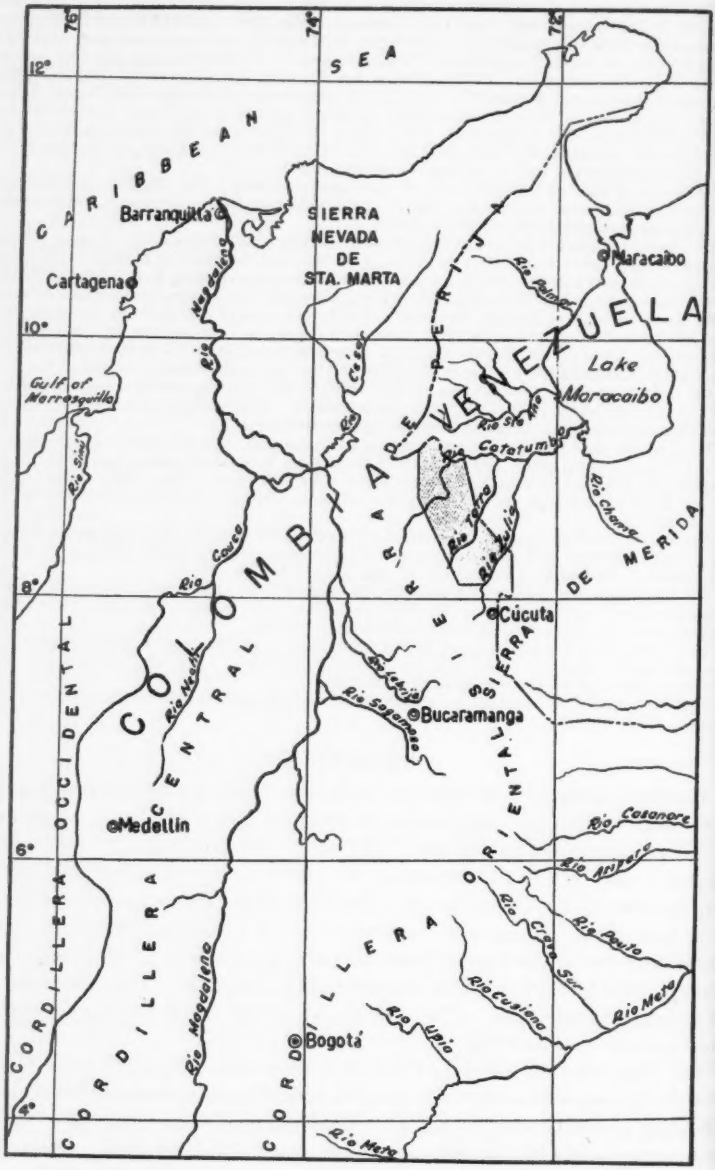


FIGURE 1.—*Map showing geographic relations of the Barco Concession*

This paper attempts to summarize the results of geological investigation of the entire original area of the Concession, plus some outside lands adjacent to the southwestern boundary.

The Concession is in the upper Catatumbo drainage basin, a wide valley and foothill area between the Sierra de Perijá on the west and the Sierra de Mérida on the southeast. The basin drains northeastward into Lake Maracaibo. Its topography is varied. Strike ridges formed by the more resistant Tertiary sandstones have a relief of 500 meters in the Petrolea area (Pl. 2, fig. 1) and of 400 meters in the Río de Oro area. In the southwestern part of the Concession, near the towns of Mercedes and Sardinata, low-dipping massive sandstones of the Tertiary form very rough topography with a relief of 1000 meters in some places and nearly vertical cliffs as high as 300 meters. Foothill ridges of Mirador standstone are often cut by slot gorges in which natural bridges are striking and rather common features. The highest known point on the Concession, near the western boundary, has an elevation of 1675 meters. In the area between the Petrolea uplift and the foothills of the Sierra de Perijá, the flood plains of the principal rivers are not over 50 meters above sea level, and the highest point in that area has an elevation of only 127 meters above sea level. The ridges forming the apical portions of the Tibú and Socuavó anticlines are not over 90 meters above sea level and rise from a gently rolling plain. In the area occupied by the low-dipping soft sediments of the Necesidad formation between Caño La Raya and the Río Catatumbo, a complex dendritic drainage system has cut the region into a maze of narrow, steep-sided ravines separated by narrow winding ridges.

The climate is wet equatorial. There is a definite wet season from October to early December, inclusive, followed by a definite dry season from mid-December through March. In normal years there is a short minor rainy season in April and May followed by showery weather through September. Within the Concession the rainfall varies from 330 centimeters (130 inches) at Petrolea to 482 centimeters (190 inches) at Río de Oro. At Petrolea over a period of 2 years the average daily maximum temperature has been 31.7° C. (89.1° F.), and the average daily minimum has been 23.3° C. (73.9° F.). Naturally, under these conditions the forest cover is a dense tropical rainforest.

When formal exploration work began in 1931 transportation facilities were confined to a mule trail from Puerto Villamizar, on the Cúcuta railway, to Petrolea and wet-season launch and barge navigation to Puerto Reyes and Puerto Barco on the Catatumbo River system. A road from the railway to the Petrolea valley was completed in 1938.

In 1931 the Concession area had no civilized inhabitants except a few scattered agricultural squatters along the southern limits. The indigenous population consisted of an estimated few hundred Motilone Indians, a tribe said to stem from the Carib strain. They cultivate *yuca* (sweet cassava), bananas, yams, sugar cane, pineapples, cotton, and peppers and live in thatch-roofed communal houses (Pl. 3, fig. 2). They have little pottery and no domestic animals. Those who live close to the rivers use rafts instead of canoes. Their only weapon is the bow and arrow with which

they are deadly at short ranges. The arrows are not poisoned but usually cause infected wounds (Salamanca, 1942). This tribe has a record of hostility to the incursions of the whites since the earliest days of the Spanish conquest (Jahn, 1927, p. 59–115). They have been gradually forced back into the foothills of the Sierra de Perijá. All efforts to make peaceful contact with them have failed. They are in strong contrast with other Indian tribes in the forest districts of Colombia, most of whom are friendly and all of whom are reasonably tractable. The Motilone is not characteristic of Colombia but is peculiar to the Sierra de Perijá and the Catatumbo jungles. Chiefly because of Indian hostility the region has remained little known and only partially explored.

All exploratory activities except in the extreme southern part of the Concession had to be conditioned to the eternal threat of ambush. All parties were armed for defense. In the more exposed areas main camps were stockaded (Pl. 3, fig. 1) and guarded at night by armed watchmen. From 1931 to 1942 geological parties lost two laborers killed by arrows; three geologists and nine laborers were wounded. The above is quite aside from casualties in other departments. In many attacks there were no casualties. The necessity of strong crews, guarded camps, escorted pack trains, guarded working crews, underbrushing both sides of trails to reduce ambush facilities, stockade construction, as well as a small wage bonus for labor working in the Indian country greatly increased the cost of exploration.

HISTORY OF EXPLORATION

From 1913 to 1931 perhaps a dozen geological parties made short reconnaissance trips into parts of this area, but we have no record of detailed studies.

Systematic exploration of the Concession as constituted under Law 80 of 1931 was begun by the Colombian Petroleum Company under the control of the Gulf Oil Corporation in July 1931. L. A. Luecke directed the first field geological party. H. D. Hedberg, assisted by C. W. Flagler, H. S. Ladd, and L. A. Young, prepared a special report in 1931 defining the preliminary stratigraphic classification of the area. This was modified in a later report by Hedberg based on additional field work and on examination of samples collected by Luecke. The stratigraphic foundation laid by Hedberg has stood, although some subdivision of units and refinements of formational boundaries resulted from later work by W. S. Olson, Flagler, and others. From 1933 to August 1938 Flagler handled subsurface work. The heavy mineral data on the section can be credited almost entirely to him. Olson replaced Luecke as Chief Geologist of the Colombian Petroleum Company in November 1933 and continued in that capacity until the Texas-Socony partnership took over the management of the Colombian Petroleum Company in October 1936. F. B. Notestein was in charge of the geological department from that time until the end of March 1938, since which time he has been retained as consultant. C. W. Hubman took charge of the geological department in April 1938 and is still in charge. J. W. Bowler has been in charge of subsurface work since the departure of Flagler in 1938.

Under the Gulf management the Colombian Petroleum Company had obtained an excellent stratigraphic foundation, had prepared detailed geological maps of the Petrolea anticline and of the Río de Oro-Puerto Barco area, and had reconnoitered

FIGURE 1.—STRIKE RIDGE OF EOCENE SANDSTONE ENCIRCLING PETROLEA ANTICLINAL VALLEY
East Barco Ridge in right background. View looking north. Dashed line outlines strike ridge.
Courtesy of Capt. W. M. Hightower.

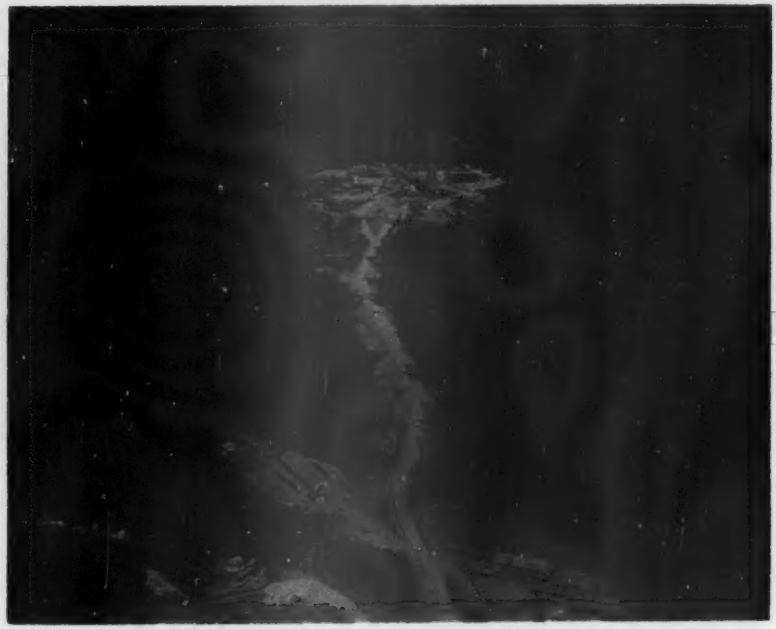


FIGURE 2.—LABORERS' CAMP AND RIG, SOCUAVO NO. 1
Topography and forest cover typical of the folds of the Sardinata depression.
Courtesy of Capt. W. M. Hightower.

TOPOGRAPHIC EXPRESSION OF STRUCTURE AND FOREST COVER AS AFFECTING EXPLORATION AND DEVELOPMENT

FIGURE 1.—STOCKADED GEOLOGICAL CAMP, SOCUAVO AREA
Photograph by J. E. Banks

FIGURE 2.—MOTILONE HOUSE AND CLEARING
Courtesy of Capt. W. M. Hightower

GEOLOGICAL CAMP DESIGNED FOR DEFENSE, AND TYPICAL MOTILONE INDIAN HOUSE

the southern and southwestern parts of the Concession as well as the upper Río de Oro as far as La Confluencia and part of the upper Catatumbo above Puerto Barco. The Sardinata basin had been crossed by two very hasty reconnaissance lines south of Puerto Reyes. North of Puerto Reyes it was unexplored except for one short line cut in from the Catatumbo. Much had been accomplished, but much remained to be done.

When the new ownership took over the management of the Colombian Petroleum Company in 1936 the geological staff consisted of Flagler, whose record in building up subsurface data had been outstanding and whom we were fortunate to retain even for a while, J. G. Schoonover, and R. E. King. Unfortunately King left in a short time, and the new geological department had to be built around a small nucleus. During 1937 and 1938 a strong geological staff was built up, and the geological mapping of all parts of the Concession of possible economic interest was completed well before the date for making final land selections in 1941. This stage of the work involved detailing large areas previously reconnoitered, as well as reconnaissance and detail of the large unexplored portions of the Concession except certain deeply incised mountain areas along the western boundary which were dropped from consideration after careful aerial inspection.

The original triangulation net of the southern part of the Concession was laid out by P. K. Anderson and was amplified and extended to the north end by Arne Birketvedt. The topographic maps prepared by the latter were of outstanding quality. In 1939 and 1940 the triangulation net of the entire Concession was revised with geodetic equipment by geodetic engineers. The earlier work came out with credit although it was, of course, of a lower order of accuracy. The triangulation net was not a geological project but is mentioned here as all the geological maps are tied to it at various points.

All the earlier geological survey lines were run with plane table and alidade as the foothill areas were rough and elevation control was necessary. When surveys of the lowlands of the Sardinata, Tibú, Nuevo, Socuavó, and Catatumbo valleys were begun it was recognized that the topographic relief was so low as to influence little the geological interpretation. Accordingly, methods were modified. Closed plane-table traverses were run on all main trails, and closed cross traverses were run at convenient intervals; then streams were traversed by Brunton compass and steel tape, with as many ties as possible to plane-table stations. In this manner much ground could be covered in a short time with a very moderate probable error. Almost all rock exposures occur in stream beds, and nearly all traverses were accomplished by wading the streams.

Aerial photographs of the southern half of the Concession were obtained in 1937 and of most of the remainder at a later date. Because of the heavy forest cover and unsatisfactory photography they were of little use except that they furnished data for maps of the larger streams in the unexplored areas. No previously unknown structural features were found by the use of photographs. The central part of the Socuavó anticline can be seen from the air if observed under optimum light and altitude conditions, but it cannot be seen in the pictures. Its south end was first observed during aerial reconnaissance.

A seismic party of the Petty Geophysical Engineering Company began work in June 1939, and a second party began work in May 1940; both continued operations until January 1941. H. M. Dawson and W. M. Krum acted as party chiefs, and A. B. Hamil acted as geophysical supervisor after the arrival of the second party. The Sardinata-Socuavó basin area proved amenable to the seismic method. The best reflection horizon was the La Luna formation of the Cretaceous. Fair reflections were also obtained from the Uribante formation and from the Tertiary below the Mirador sandstone. Where surface data were available the check with seismic data was reasonably consistent. A satisfactory structural picture was obtained by seismic work in considerable areas covered by alluvium.

This was an exploration project somewhat out of the ordinary with a corresponding appeal to anyone with a trace of the pioneering instinct. The job was largely just plain hard work, but there was the challenge of an unexplored area and frequently a spice of danger. The men worked at all times under difficult conditions, sometimes under extreme conditions. The work was carried forward cheerfully and stubbornly because professional pride was involved in the completion of a difficult assignment. The geological staff, exclusive of the men in charge already mentioned, which did the systematic work on the Concession between 1931 and 1942, is listed below in alphabetical order. This is hardly adequate recognition, but there are so many names that it seems impossible to handle the matter in any other way.

Party Chiefs: Robert Allan, V. A. Bray, H. V. Lee, C. L. Lee, C. W. Saville, J. G. Wilson, T. C. Wilson.

Assistant Geologists: J. E. Banks, A. L. Bell, M. W. Garber, J. de Mier Restrepo.

Topographers: A. Birketvedt, Paul Morris, J. G. Spoerry, Randolph Winslow.

Subsurface Geologists: H. W. Anisgard, H. T. Baldwin, C. DeBlieux, P. B. Fahle, R. E. King, J. B. Petta, J. G. Schoonover, C. G. Spencer, F. E. Vandenberg, G. H. Wolf.

The authors of this paper have drawn with complete freedom on all reports in the files of the Colombian Petroleum Company, and the present summary is a compilation of the studies of all those who worked on the project. Grateful acknowledgment is made to all of them. Special acknowledgment is due H. D. Hedberg for careful review of the manuscript and for various helpful suggestions regarding stratigraphy.

METAMORPHIC AND IGNEOUS ROCKS

Within and adjacent to the Concession, a complex of metamorphic and igneous rocks underlies Lower Cretaceous sediments. This basement has been reached in four wells, Petrolea Nos. 1-A and 95, Socuavó No. 1, and Tres Bocas No. 2-A, and in these it consists of highly contorted schists and chloritic quartzites. West of the Concession, in the Sierra de Perijá, the Cretaceous is in depositional contact with acidic igneous as well as metamorphic rocks. No igneous intrusions of Cretaceous or younger sediments have been noted.

The age of the basement rocks is not known. Existence of less metamorphosed Devonian sediments in the Sierra de Perijá (Liddle, 1928, p. 97–98) suggests a pre-Devonian age. The basement had evidently been reduced to low relief in this particular area before incursion of the Lower Cretaceous sea, judging from the uniform thickness and development of Lower Cretaceous rocks (Fig. 4).

STRATIGRAPHY

GENERAL

The sedimentary section on the Concession begins with Lower Cretaceous rocks. The red beds which underlie the Cretaceous in large areas of Colombia have not been found on the Concession although they are known to be thick and widely distributed in the Sierra de Perijá and the Sierra de Mérida. These red beds have long been commonly referred to as the Girón formation. Unfortunately, this term has been loosely applied in various parts of Colombia to red sediments now known to range in age from Devonian to Lower Cretaceous. Absence of red sediments on the Concession suggests, although it does not prove, a rather prolonged erosion interval prior to the incursion of the Lower Cretaceous sea.

The accompanying generalized columnar section (Fig. 2) shows the 14 formations recognized on the Concession. Suggested correlations with western Venezuela and the Magdalena valley are shown in Figure 3. Plate 1 shows the areal geology of the Concession and place names referred to in the text.

The Lower Cretaceous, which is entirely marine, averages about 700 meters in thickness and consists of the Uribante and Cogollo formations. The Upper Cretaceous, which is dominantly marine but includes some brackish-water deposits in its upper part, is approximately 950 meters thick and is divided into the La Luna, Colón, Mito Juan, and Catatumbo formations.

No unconformity is known to separate the Cretaceous and Tertiary systems; the change is transitional, and doubt exists as to the exact location of the Cretaceous-Eocene contact. The uppermost Mito Juan (as defined on the Concession) is definitely Maestrichtian in age, and fossils from the Catatumbo, although not definitely diagnostic, suggest that this formation also is Cretaceous. Accordingly, the Cretaceous-Eocene boundary has been tentatively drawn at the top of the Catatumbo.

The Tertiary rocks, which are characteristically nonmarine but carry a few marine beds, are approximately 2500 meters thick within the limits of the Concession and are divided into the Barco, Los Cuervos, Mirador, Carbonera, León formations, the Guayabo group, and the Necesidad formation. A major coal series occurs in the bottom part of the Los Cuervos. If the remainder of the Guayabo group as known outside the Concession is included, the thickness of the Tertiary would be increased 75 per cent. Eocene, Oligocene, and Miocene are present, with the youngest rocks belonging to either the Pliocene or Pleistocene.

Within the Concession, no major unconformities have been demonstrated for the Tertiary below the Miocene Guayabo group. However, a minor unconformity occurs at the base of the Mirador at least locally, and there may be another unconformity at the top of this formation. The Mirador marks a strong change in sedimentation for the region, showing as it does a veritable flood of coarse clean sands, the first appearance of such following Lower Cretaceous time. The Necesidad formation rests with a strong angular unconformity on the Guayabo group.

CRETACEOUS SYSTEM

Uribante formation (*Lower Cretaceous*).—The name of the Uribante formation is taken from the Río Uribante, State of Táchira, Venezuela. The name was first applied by Sievers (1888, p. 19).

AGE
FORMATION
THICKNESS (in meters)
Recent
Alluvium
Pliocene
Necesidad
Variocolored claystones and clays with friable fine to very coarse sandstones
Miocene
Guayabo Group
800+
Buff and gray friable sandstones with locally mottled claystones
Light-gray and green dull mottled claystones with some sandstones
Buff and gray friable sandstones and sandy shale
Oligocene
Leon Shale
350-765
Gray and green-gray shale. Locally some thin sandstones near middle
Carbonera
410-720
Gray commonly yellow and red mottled claystones with beds of argillaceous sandstones. Thin lignitic coals near top and bottom
Eocene
Mirador
150-450
Light-buff to white massive fine to coarse sandstone. Clean and locally contains small pebbles. Few beds of gray and brown-gray shale
Los Cuervos
230-490
Gray and green-gray claystones with red and yellow mottling. Beds of green-gray argillaceous sandstones
Dark-gray carbonaceous shales and claystones with beds of sandstone and coal
Barco
75-275
Gray very fine to medium argillaceous sandstones and dark-gray claystones and shales. Cleaner "sparkling sandstones" in middle and lower parts. Little coal
Upper Cretaceous
Catatumbo
100-270
Dark-gray carbonaceous shales and claystones with some sandstones. Some thin coals Glauconitic and foraminiferal in lower part
Mito Juan
270-420
Greenish-gray very sparsely foraminiferal silty shale. Glauconitic fossiliferous limestones in upper part
Colon
210-450
Dark-gray slightly calcareous foraminiferal shale. Zone of sandy glauconite at base
Lo Luna
45-85
Hard dark-gray limestones and black bituminous calcareous shales. Limestone concretions. Abundant pelagic Foraminifera Some black chert
Lower Cretaceous
Cogollo
220-440
Gray crystalline fossiliferous limestones and black shales. Some siltstone
Black non-calcareous shales. Few beds of limestone and siltstone. Calcareous and foraminiferal zone at base
Dark-gray limestones and platy black shales with abundant Foraminifera
Uribante
420-500
Hard gray and greenish fine to coarse cross-bedded glauconitic and calcareous sandstones. Some black shale and few beds of limestone in bottom
Gray dense fossiliferous limestones and black shales. Considerable amount of highly calcareous glauconitic sandstone
Gray dense fossiliferous limestones with some shale and sandstone. Coarse pebbly sandstone at base
pre-Cretaceous
Igneous and metamorphic

FIGURE 2.—*Composite columnar section of the formations exposed on the Barco Concession*

LITHOLOGY: On the Concession the formation is divided into the Tibú, Mercedes, and Aguardiente members, in ascending order (Fig. 4).

The Tibú member has at its base a sandstone 5 to 12 meters thick representing the initial Uribante deposit. It is coarse-grained and contains small pebbles of quartz and a few of orthoclase in the lower part, the pebbles rarely attaining 2 centimeters in diameter. It becomes fine-grained and calcareous at the top. Cores of the basal sandstone from Tres Bocas No. 2-A are somewhat carbonaceous. Overlying the

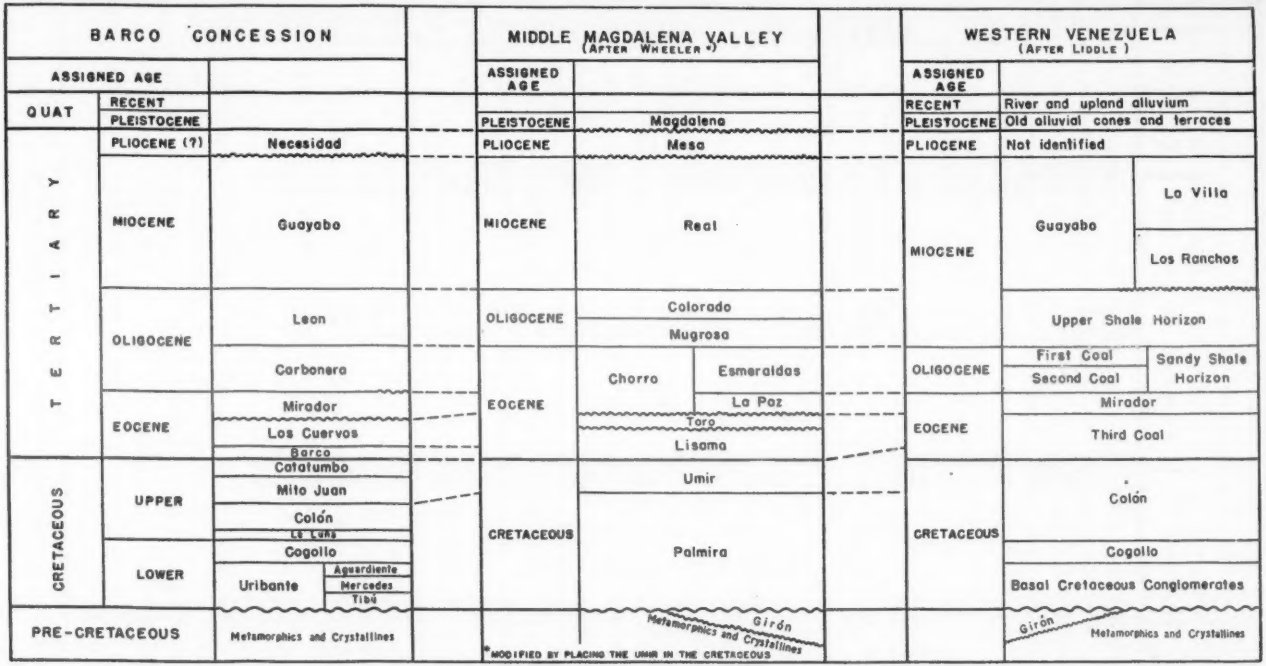


FIGURE 3.—*Suggested correlations between Barco Concession section, Wheeler's Magdalena valley section, and Liddle's western Venezuela section*
Dashed lines show authors' ideas of equivalencies.

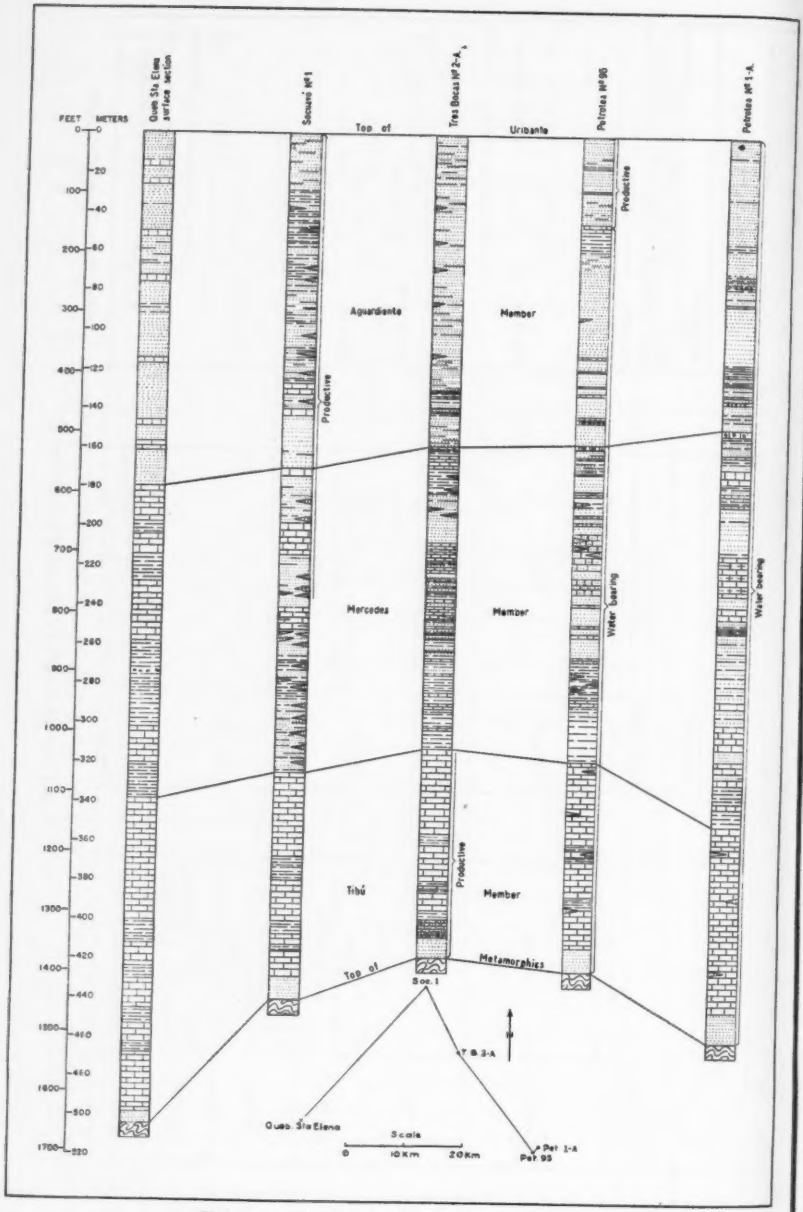


FIGURE 4.—*Correlation chart of Uribante sections*

basal sandstone is 95 to 160 meters of gray densely crystalline fossiliferous limestone, containing some shale and fine-grained sandstone in its lower half. The upper 50 meters of this member is practically all limestone, and its top is sharply limited by a change to shale. This sharp contact has appeared in all well sections. The thickness of the Tibú member ranges from 107 to 117 meters in wells, but in Quebrada Santa Elena it appears to be 166 meters thick. The entire Uribante formation is thicker in that section and shows more limestone than in the well sections. The Tibú member crops out in the headwaters of the Río Tibú, from which it takes its name. It first attained importance when found to be productive of oil on the Tibú anticline.

The Mercedes member is composed of interbedded limestones, shales, and sandstones with beds commonly ranging from 3 to 20 meters in thickness. The limestones are similar to those in the Tibú member but are in part arenaceous. The shales are generally black, micaceous, and carbonaceous, but some beds are dark gray, and some are very calcareous. Shales compose a large part of the lower third of the member. The sandstones, which are subordinate in amount, are gray, fine to medium grained, commonly glauconitic, and in part very calcareous. They are nearly twice as abundant in the upper half of the member as in the lower half. The top of the Mercedes member is drawn where limestones and shales become predominant over sandstones, but no sharp break exists below the overlying Aguardiente member. The thickness of the Mercedes member ranges from 149 to 201 meters in well sections and is about 160 meters in Quebrada Santa Elena. The member is named from the Mercedes valley, along the west side of which it is exposed.

The Aguardiente member is composed almost entirely of extremely hard and calcareous gray or light-green fine- to coarse-grained cross-bedded glauconitic sandstones. As known from wells the upper 10 meters is relatively free from glauconite, but this mineral is common throughout the remainder of the member. Interbedded with the more glauconitic sandstones are gray, only slightly glauconitic sandstones with micaceous-carbonaceous partings. Some thin laminae and beds of black micaceous-carbonaceous shale are present, and a few thin beds of limestone occur in the lower part. Locally the sandstones are so calcareous as to approximate arenaceous limestones. The thickness of the Aguardiente member ranges from 148 to 160 meters in well sections and Quebrada Santa Elena. The member is named from the Filo del Aguardiente. This topographic feature is an impressive dip slope on the northern part of the Santiago dome, extending from approximately 450 to 2000 meters elevation, formed by the resistant upper Uribante sandstones. There the Aguardiente member is considerably thicker than on the Concession, and 25 kilometers still farther south, on the Río Peralonzo, 275 meters was measured.

THICKNESS: The total thickness of the Uribante formation ranges from 418 to 459 meters in well sections and is 503 meters in Quebrada Santa Elena. South of the Concession, on the Río Peralonzo, a thickness of 825 meters has been reported.

PRODUCTIVE CHARACTER: Production is obtained from all three members of the Uribante formation in the Tibú-Socuavó area, but only the Aguardiente member is productive on the Petrolea North Dome. Analyses of 280 core samples of Uribante sandstones show characteristic permeabilities of less than 10 millidarcys and porosities ranging from 0.5 to 14 per cent, with an average of 5.5 per cent. In view of core data,

fractures must be considered to explain the production obtained from the Uribante, whether from sandstones or from dense limestones. Well behavior supports the belief that fractures are of primary importance. In the Tibú limestones of Tres Bocas No. 2-A fractures show clear evidence of having been enlarged by solution. The outcrops of some of the limestones and shales of both the Tibú and Mercedes members are petroliferous; several samples from Quebrada Santa Elena yielded positive chloroform cuts.

Boundaries and Relationships: The Uribante formation rests unconformably on the basement of metamorphic and igneous rocks. The top of the formation is drawn where the sandstones give way to the foraminiferal limestones and shales of the lower member of the overlying Cogollo formation. This is a conformable contact, generally with a suggestion of gradation.

Heavy Minerals: The Uribante contains a heavy-mineral assemblage known as the zircon-leucoxene suite, a suite characteristic of the whole Lower Cretaceous of this region. The suite is characterized by simplicity of mineral content, generally well rounded grains, abundance of zircon and leucoxene, and absence of garnet, chloritoid, and staurolite.

Age and Origin: The Lower Cretaceous age of the Uribante formation in the State of Táchira, Venezuela, has been established by H. S. Ladd,[1] who also reported molds of *Exogyra* aff. *boussingaulti* and other Cretaceous oysters in an exposure of the Aguardiente member near the town of Gramalote just south of the Concession. R. B. Wheeler of the Texas Petroleum Company found a fossil locality in the Tibú member at a point 13 kilometers south of the town of Sardinata carrying a fauna of mollusks and echinoids. His collection was submitted to H. E. Vokes, then Associate Curator of Fossil Invertebrates, American Museum of Natural History, who classified the fauna as of "Aptian age (possible Upper Aptian or Lower Albian)" (W. C. Hatfield, personal communication). A further collection from the same locality was submitted to T. J. Etherington of the Richmond Petroleum Company, Bogotá, Colombia, who concludes that the echinoids are younger than those of the basal Cretaceous of the Sogamoso River section (considered Valanginian on the basis of ammonites) and are of "possible Aptian age" (personal communication). As the overlying Cogollo formation is considered to be of Aptian-Albian age the indications are that the entire Uribante formation is of Aptian age.

Fossils clearly establish the marine origin of the Uribante.

Correlation: The Uribante may be correlated directly with the Uribante, Tomón, and Río Negro conglomerate formations of western Venezuela, as well as with the Barranquín formation of eastern Venezuela (Hedberg and Sass, 1937, p. 77).

Occurrence: The Uribante crops out in the extreme southern part and along the western side of the Concession. It or its equivalents are widely distributed in the Sierra de Perijá and the Sierra de Mérida. It is safe to consider that on the Concession the Uribante everywhere underlies the younger Cretaceous rocks.

Cogollo formation (*Lower Cretaceous*).—The name of the Cogollo formation is taken from the Río Cogollo, District of Perijá, Venezuela, and the type section is on this river near the eastern border of the Sierra de Perijá. Hedberg and Sass (1937, p. 77)

[1] Private report of the Venezuelan Gulf Oil Company.

report that the formation was probably named by geologists of the Caribbean Petroleum Company.

LITHOLOGY: On and adjacent to the Concession the Cogollo formation is composed principally of dark-gray to black fissile shales with interbedded gray to dark-gray fossiliferous limestones and a very minor amount of gray argillaceous siltstones. In the Petrolea area, where 32 wells have penetrated the entire thickness of the Cogollo, the formation is divided into the Lower Cogollo, Middle Cogollo, and Guayacán members, but such detailed subdivision is not applicable throughout the Concession (Fig. 5).

The Lower Cogollo consists of black very calcareous organic and bituminous foraminiferal thin-bedded shale and dark-gray foraminiferal limestone. Some macrofossils are present. The member comprises approximately one-fifth of the entire formation and is distinguishable in all sections. The upper contact of the member is transitional and is drawn at the top of the first limestone below the thick shales of the Middle Cogollo.

The Middle Cogollo member consists of dark-gray to black noncalcareous shale and a few beds of gray argillaceous fossiliferous limestone and, locally a few beds of siltstone and silty shale. The member is well developed in the Petrolea area, where it comprises approximately three-fifths of the formation, but the top of the member is not distinguishable elsewhere owing to the poor development of limestones in the Guayacán member. The top of the middle member is sharply drawn in Petrolea wells at the base of a 3- to 7-meter bed of limestone forming the base of the overlying Guayacán member.

The Guayacán member, named from Quebrada Guayacán in a branch of which it crops out on the Petrolea South Dome, consists of brownish-gray abundantly fossiliferous fairly thick, massive limestones with interbedded dark-gray to black noncalcareous in part silty and micaceous shales and a very small amount of gray argillaceous siltstone. In the Petrolea area nearly half the member is composed of limestone, but elsewhere the uppermost part of the Cogollo is predominantly shale.

THICKNESS: The total thickness of the Cogollo formation is best known from well sections, the shaly nature of much of the formation and complications due to faulting having rendered outcrop measurements somewhat dubious. On the Petrolea anticline unfaulted sections range from 250 to 273 meters in thickness. One well on the Tibú anticline and one on the Socuavó anticline have drilled through the formation, and these show thicknesses of 225 and 218 meters respectively. Two wells on the Río de Oro anticline show an average thickness of 175 meters. A thickness of 350 meters was measured in Quebrada Santa Elena, and a thickness of 435 meters was found in Caño Agua Sal. Possibly the Cogollo is thicker in the vicinity of these outcrop sections, but probably the true thickness is less than the surface measurements would indicate.

The formation is as a whole thinner than the minimum figure of 370 meters given for its thickness in the type section (Hedberg and Sass, 1937, p. 77). This decreased thickness is accompanied by a decrease in the proportion of limestone. The Cogollo in its type section and the equivalent Capacho formation of Táchira, Venezuela, both contain more limestone than is found in the Cogollo on the Concession.

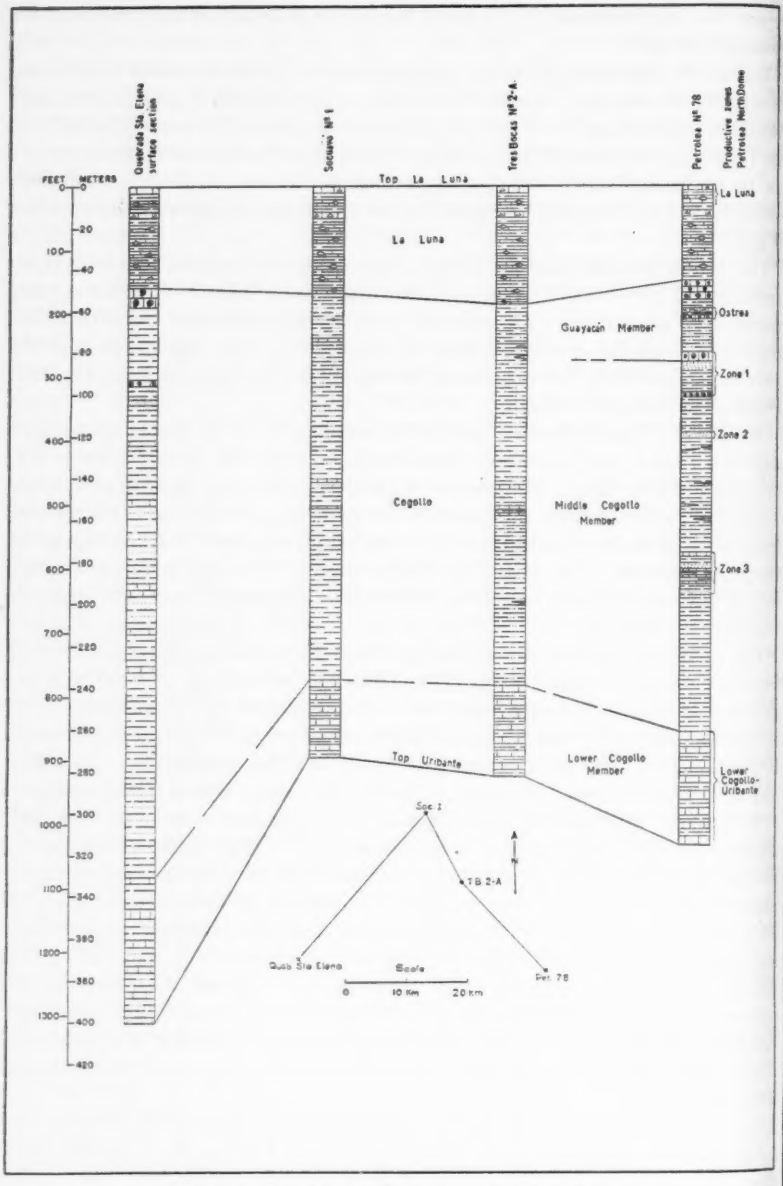


FIGURE 5.—*Correlation chart of La Luna-Cogollo sections*

PRODUCTIVE CHARACTER: Production is obtained from all three members of the Cogollo formation on the Petrolea anticline; five productive zones are recognized (Fig. 5). The siltstones and limestones have a permeability of less than 1 millidarcy. Accordingly, it is believed that production from the Cogollo is controlled by fractures, and this belief is supported by well behaviour. As a whole the Cogollo formation is richly organic, hence the petroleum is probably indigenous to the formation.

The fractured limestones of the Lower Cogollo member are productive on the crestal portion of the Petrolea North Dome. They are considered to be in communication with the underlying sandstones of the Uribante formation, and the two are produced together.

The limestone-siltstone-shale unit near the middle of the Middle Cogollo member composes Petrolea Zone 3, the most extensive producing zone on Petrolea North Dome.

Petrolea Zone 2 is composed of dark-gray argillaceous siltstones which are present over much of the Petrolea North Dome field. These siltstones range from laminae to 6 meters in thickness and occur from 25 to 30 meters below the top of the Middle Cogollo member. They are only locally productive and are not present on the Petrolea South Dome.

Petrolea Zone 1 is composed of a 3- to 7-meter limestone at the base of the Guayacán member, a siltstone at the top of the Middle Cogollo ranging in thickness from laminae to 7 meters, 10 to 20 meters of shale, and a 1-meter bed of cherty limestone. The top limestone is thought to be the main source of production from the zone.

About 15 meters below the top of the Cogollo is the so-called *Ostrea* zone, a zone productive in the crestal area of Petrolea North Dome. In the northern and central parts of the North Dome field the *Ostrea* zone consists of 3 to 5 meters of limestone in one or two beds, in the latter case with 0.3 to 2 meters of shale and siltstone between the limestone beds. In the southern part of the field the limestones of the zone are as much as 9 meters apart, and locally more than two limestones are present.

BOUNDARIES AND RELATIONSHIPS: The base of the Cogollo formation is conformable with the underlying Uribante, the contact varying from sharp to moderately gradational. The top of the Cogollo is conformable with the overlying La Luna formation. A sharp division exists between these two formations on and adjacent to the Concession, but this condition is not general (Hedberg, 1931, p. 238). In Petrolea the gray coarsely crystalline limestone at the top of the Cogollo gives way abruptly to the La Luna type of sediments; on the Tibú, Sardinata, and Rio de Oro anticlines dark-gray noncalcareous nonforaminiferal shale typical of the Cogollo formation is in contact with the La Luna. In the last three areas there are a few thin beds of La Luna-like, foraminiferal limestone in the upper part of the Cogollo.

HEAVY MINERALS: Most of the Cogollo formation is too fine-grained for heavy-mineral study. However, the siltstones yield mineral assemblages essentially the same as those from the Uribante and clearly belong to the zircon-leucoxene suite.

AGE AND ORIGIN: The Lower Cretaceous age of the Cogollo formation has been established by many workers. Liddle (1928, p. 136, 149) refers it to Aptian-Albian. Hedberg and Sass (1937, p. 78) call it Aptian-Albian "possibly extending as high as

Cenomanian." Outcrops on the Concession have yielded abundant specimens of *Cardita subparallela*. Well cores indicate that this form is not very abundant below the upper part of the Middle Cogollo and is most abundant in the Guayacán member. Specimens of *Cyprimeria* and *Poromya* are common. *Plicatula "maraensis"* is abundant in the limestones and is associated with other well-known genera such as *Corbula*, *Gryphaea*, *Inoceramus*, and *Trigonia*. The fauna clearly establishes the marine origin of the formation.

CORRELATION: The Cogollo may be correlated directly with the Cogollo formation of western Venezuela and is equivalent to the Capacho formation of Táchira, Venezuela. It may be correlated with part of the Villeta formation of Colombia and also with the El Cantil formation of eastern Venezuela.

OCCURRENCE: The Cogollo crops out in the southern and western parts of the Concession and is widely exposed along the eastern border of the Sierra de Perijá. It is believed to underlie the younger Cretaceous rocks everywhere on the Concession.

La Luna formation (Upper Cretaceous).—The type section and type locality of the La Luna formation are in the District of Perijá, Venezuela. According to Hedberg and Sass (1937, p. 79), La Luna is the name of a cattle ranch situated about 16 kilometers northwest of La Villa del Rosario; the type section is in Quebrada La Luna just northwest of this ranch. The name was probably first used by geologists of the Caribbean Petroleum Company.

LITHOLOGY: On the Concession the La Luna consists of hard dark-gray abundantly foraminiferal limestones and hard black highly calcareous platy bituminous shales. Bands and nodules of black chert are present in very minor amount, more numerous in the upper part. Outcrop sections suggest more chert in the upper part of the La Luna than displayed by well sections. Concretionary masses of dense gray limestone, ranging from a few centimeters to 75 centimeters in size, are characteristic of the formation. The character of the La Luna and the means of distinguishing this formation from the Cogollo have been very completely described by Hedberg (1931, p. 231–238).

THICKNESS: The La Luna formation is very uniform in thickness, particularly on the Petrolea anticline where it ranges from 43 to 49 meters in thickness in wells on the North Dome; on the Petrolea South Dome its thickness is about 55 meters. Farther south comparable thicknesses were measured in Caño Agua Sal and in Quebrada Pedragosa, near Astillero. The formation was logged as 56 meters thick on the Tibú anticline and 51 meters thick on the Socuavó anticline. In Quebrada Santa Elena it is 49 meters thick. A thickening to the north is indicated by an average thickness of 86 meters in two wells on the Río de Oro anticline. This compares with the much greater thickness of nearly 300 meters of the type section (Hedberg and Sass, 1937, p. 79) still farther north.

PRODUCTIVE CHARACTER: The La Luna is characteristically bituminous and rich in organic remains, and many of the limestones are largely composed of pelagic Foraminifera. Hedberg (1931, p. 231–239) has presented reasons for considering the formation an important source of petroleum. Production is obtained from fractured La Luna in shallow wells on the crestal area of Petrolea North Dome.

BOUNDARIES AND RELATIONSHIPS: The La Luna rests conformably upon the Co-

gollo formation, and the contact is easily drawn. The top of the La Luna is conformable with the overlying Colón shale and is locally somewhat gradational; the topmost La Luna contains glauconitic material similar to that which forms the basal part of the Colón shale.

HEAVY MINERALS: The formation is too fine-grained for heavy-mineral study.

AGE AND ORIGIN: The La Luna is Upper Cretaceous, approximately Turonian (Hedberg and Sass, 1937, p. 80) on the basis of *Inoceramus labiatus*, specimens of which were identified by H. S. Ladd from samples collected on the Concession. However, it may include part of the Cenomanian and Coniacian.

CORRELATION: The La Luna is approximately the equivalent of the Táchira formation of western Venezuela and of the Guayuta formation of eastern Venezuela. It is equivalent to part of the Villeta formation of Colombia.

OCCURRENCE: The formation crops out in the southern and western parts of the Concession and is well exposed along the eastern border of the Sierra de Perijá.

Colón shale (Upper Cretaceous).—The type locality of the Colón shale is believed to be the town of Colón, State of Táchira, Venezuela. According to Hedberg and Sass (1937, p. 81) the name was introduced many years ago by geologists of the Shell companies. It has since been widely and loosely used for Upper Cretaceous shales in western Venezuela. The name is now well established.

LITHOLOGY: The formation is composed of gray to dark-gray slightly calcareous fissile moderately foraminiferal shale. Thin nodules and lenses of brown clay-ironstone are locally developed. At the base, immediately above the La Luna, there is a 2- to 5-meter zone of sandy glauconite, reworked Foraminifera, abundant fish remains, and round rods and pellets which may be coprolites. Immediately above this thin glauconitic zone an interval of highly pyritic shale is commonly 3 to 5 meters thick. Purely on a basis of Foraminifera an upper and a lower division of the Colón are recognized. The formation contains a very few thin beds of limestone on the Río de Oro anticline, and limestone beds are known in the formation in western Venezuela. However, the Colón is normally free from limestone within the Concession.

THICKNESS: The most reliable thickness figures for the Colón shale on the Concession are those from wells. In Petrolea wells it commonly ranges from 215 to 245 meters in thickness in what are believed to be unfaulted sections; 306 meters and 334 meters were logged on the Tibú and Socuavó anticlines respectively; the thickness on the Río de Oro anticline is from about 400 to 460 meters. Thickening to the north is accompanied by a proportional thinning of the overlying Mito Juan formation. A thickness of 425 meters of Colón shale was measured in Quebrada Santa Elena, but in view of the erroneously high surface measurements of the same formation in the Petrolea area the thickness in the Santa Elena area is perhaps questionable. In Petrolea the lower foraminiferal zone is generally from 120 to 140 meters thick, and the upper zone is 90 to 105 meters thick. The zones are approximately equal in thickness in wells north of the Petrolea area, but there the total thickness of the Colón is greater.

BOUNDARIES AND RELATIONSHIPS: The base of the Colón shale may be drawn quite sharply at the top of the La Luna limestones. The contact is believed to be essentially conformable. The top of the Colón is drawn on the basis of Foraminifera;

a moderately abundant and varied assemblage of Foraminifera in the upper Colón shale gives way rather abruptly to a scanty microfauna which characterizes the overlying Mito Juan formation. The top contact is conformable.

The glauconitic zone at the base of the Colón shale is of wide distribution. It has been found in all wells on the Concession which drilled this part of the section and is present in Quebrada Santa Elena and also in the Mercedes area. It is known to be developed in the State of Táchira, Venezuela. Its presence, coupled with a thinner La Luna formation on the Concession than found elsewhere, early led to speculation concerning a possible unconformity between the La Luna and the Colón formations. However, the extremely uniform thickness of La Luna in wells on the Petrolea, Tibú, and Socuavó anticlines and a comparable thickness in Quebrada Santa Elena (Fig. 5) and other outcrops scarcely fit the hypothesis of an erosional unconformity. Also, some local interbedding of the glauconitic sediments in the uppermost La Luna does not support such an explanation. Cushman and Hedberg (1941, p. 80) suggest a possible hiatus between La Luna and Colón or a stratigraphically condensed section in the lowermost part of the Colón.

HEAVY MINERALS: The formation is too fine-grained for heavy-mineral study.

AGE AND ORIGIN: The Colón shale has been definitely established as of Upper Cretaceous age. Cushman and Hedberg (1941, p. 79–100) classify the lower member of the Colón as of Taylor age and the upper member as of Navarro age (Senonian). They list as distinctive of the lower or *Pullenia cretacea* zone: *Pullenia cretacea*, *Gyroidina globosa*, *Siphogenerinoides cretacea*, *Haplophragmoides flagleri*, and *Dorothia* cf. *filiformis*. Similarly listed for the upper or *Siphogenerinoides bramlettei* zone are: *Siphogenerinoides bramlettei*, *Allomorphina velascoensis*, *Pseudoglandulina lagenoides*, *Marginulina silicula*, *Loxostoma plaitum*, and *Planulina correcta*. H. S. Ladd[2] reported finding well-preserved ammonites, in addition to *Inoceramus*, *Leda*, *Pinna*, etc. The formation is of marine origin with probably an approach at times toward brackish-water conditions during the deposition of its uppermost part.

CORRELATION: The Colón shale as defined on the Concession is in general equivalent to the Colón shale of Venezuela. However, it is not Liddle's Colón formation which includes the Colón shale, Mito Juan, and La Luna formations as defined herein.

OCCURRENCE: The formation crops out in the southern and western parts of the Concession and is widely distributed along the eastern border of the Sierra de Perijá.

Mito Juan formation (Upper Cretaceous).—The Mito Juan formation is named from Quebrada Mito Juan (frequently spelled Mita Juan) on the Petrolea North Dome. The type section is in this stream on the east flank of the Petrolea anticline, about 2 kilometers east of the axis. Hedberg and Sass (1937, p. 83) report that the name was probably first applied by geologists of the Caribbean Petroleum Company.

LITHOLOGY: The formation consists dominantly of greenish-gray shales, silty shales, and some sandy shales; silt and sand increase upward, and some thin beds of siltstone and very fine-grained sandstone have been found near the top. Thin lenses and smaller nodular masses of brown clay-ironstone are common. In the lowermost part there are some gray and dark-gray shales like the Colón shales, but commonly they are noncalcareous whereas the Colón is typically very slightly calcareous. In

[2] Private report of the Venezuelan Gulf Oil Company.

the upper part of the shale sequence there are some more or less well-developed thin beds of glauconitic sandy fossiliferous ferruginous limestone. Small Foraminifera are not uncommon but are much rarer than in the Colón shale, and arenaceous forms predominate. Although the Mito Juan shales differ somewhat in lithology from the Colón, particularly in the predominance of greenish tinges and light grays, it is scarcely practicable to map them in the field on this basis.

Thin limestone beds are fairly numerous in the upper 200 meters of the Mito Juan on the Río de Oro anticline; they are best known from two wells which drilled the entire formation on this structure. Largely on the basis of these well sections, this part of the Mito Juan was tentatively assigned formational rank and given the name Río de Oro formation. However, the limestones are very poorly developed on the Socuavó and Tibú anticlines and are apparently represented by only a few thin beds at the top of the Mito Juan in the Petrolea area. In Leoncito No. 1 two 30-centimeter beds of limestone, separated by 15 meters of shale, are the sole representatives of the Río de Oro. In view of the decrease of limestones to the south and also because of difficulty in drawing a satisfactory contact between the Mito Juan formation and the Río de Oro, it has been decided that within the Concession the limestones may best be considered as a facies development of the upper Mito Juan. Accordingly the top of the Mito Juan has been drawn at the top of this glauconitic limestone facies.

THICKNESS: The formation ranges from 275 to 420 meters in thickness, with surface measurements showing 275 to 400 meters on the Petrolea North Dome. None of the wells in the Petrolea field began drilling above the Mito Juan, so no complete well sections are available in that area. Wells show thicknesses of 351 to 420 meters on the Tibú, Socuavó, and Río de Oro anticlines. In Quebrada Santa Elena it was measured as 402 meters thick.

PRODUCTIVE CHARACTER: A thin sandstone in the Río de Oro facies of the uppermost Mito Juan is productive on the Río de Oro anticline.

BOUNDARIES AND RELATIONSHIPS: The Mito Juan formation conformably overlies the Colón shale, and the contact can be drawn rather sharply on the basis of Foraminifera. The top of the Río de Oro glauconitic limestone facies marks the top of the Mito Juan formation, and the contact is believed to be conformable with the overlying Catatumbo formation.

HEAVY MINERALS: A depleted garnet-chloritoid suite characterizes heavy-mineral assemblages of sandy sediments of the Mito Juan. Both garnet and chloritoid become rare or absent toward the base, but there is definite affinity to the widespread garnet-chloritoid suite which characterizes the lower Tertiary of the region. This mineral suite is distinguished from the zircon-leucoxene suite by the presence of chloritoid and garnet, the latter characteristically an etched or dodecahedral variety (Hedberg, 1928, p. 41), and by a somewhat smaller proportion of zircon and leucoxene.

AGE AND ORIGIN: The Mito Juan formation is of Upper Cretaceous age. Hedberg and Sass (1937, footnote, p. 86) report that ammonites collected from the Río de Oro member of the Mito Juan formation in Quebrada del Rancho on the Petrolea anticline were identified by Dr. Spath of the British Museum as *Sphenodiscus* and *Coahuilites* and that he definitely classifies the fauna as Maestrichtian in age. The

Mito Juan formation is included in the *Ammobaculites colombianus* zone (Cushman and Hedberg, 1941, p. 80), the base of which coincides with the base of the Mito Juan. The top of this foraminiferal zone, however, extends as much as 90 meters above the top of the Mito Juan as here defined. Cushman and Hedberg remark that the arenaceous Foraminifera, particularly *Ammobaculites colombianus* and an associated *Haplophragmoides*, characterize the zone, with rarely *Vaginulina navarroana*, *Gümbelitria cretacea*, and a few other calcareous forms. The Upper Cretaceous microfauna indicates a mainly brackish-water origin for the formation. However, the Río de Oro glauconitic limestone facies at the top of the Mito Juan is marine. Two samples of these limestones, collected in the Puerto Salado area, were submitted to A. A. Olsson, who identified (personal communication) the fauna as Maestrichtian in age. Identified in the samples were: *Cardium brüggeni* (Olsson MS) [as *Cardium Lissoni* Brüggen in Olsson (1934, p. 52, Pl. 5, fig. 3)], *"Cytherea" auca*, *Venericardia* sp. (somewhat different from a *Venericardia* identified at the same time in a sample from the Catatumbo formation), *Pholadomya* sp., *Trinacria* sp. (a species found in the Umir), *Liopista* or young *Pholadomya*. Several ostracods, fragments of the test and spines of a sea urchin, and pieces of *Pecten* shell were also found.

CORRELATION: The Mito Juan formation as recognized on the Concession is largely equivalent to the Mito Juan formation of western Venezuela. However, the top of the formation in Venezuela is known to be at least locally drawn close to or at the upper limit of the *Ammobaculites colombianus* zone, or considerably higher than the limestone facies used to mark the top of the formation on the Concession. The Mito Juan may be correlated with part of the Umir formation of Colombia.

OCCURRENCE: The formation crops out in the southern and western parts of the Concession.

Orocué group (*Upper Cretaceous and lower Eocene*).[3]—Conformably upon the Mito Juan formation is a series 500 to 600 meters thick of alternating shales, claystones, and sandstones, containing some coal seams. This series is largely composed of brackish-water and nonmarine deposits, but marine beds occur in at least the lower part. The sequence takes its name from and is believed to correlate with the "Orocué" formation, a manuscript name applied by Hedberg to a formation in the Department of Santander, Colombia. The name is referred to by Cushman and Hedberg (1941, p. 79). However, for purposes of detailed mapping and because the lithology of the sequence permitted, the "Orocué" was subdivided into three new formations by W. S. Olson. These formations are, from oldest to youngest, Catatumbo, Barco, and Los Cuervos.

Catatumbo formation (*Upper Cretaceous*).—The Catatumbo formation is named from the Río Catatumbo, along which the formation crops out for some distance between Barranca Bermeja and Puerto Salado. However, the exposures along the river are not satisfactory as a type section, and the section logged in Oro No. 3, located 10 kilometers northeast of the type locality, is used instead. A considerable part of the Catatumbo was cored in this well, and the formation was also cored and

[3] The name is included here and is shown on the map legend because the mapping of a portion of the southern part of the Concession was never fully revised after this subdivision was made, and the group appears as a stratigraphic unit on the map, (Pl. 1), from Cerro Gonzalez to Quebrada Agua Sal.

drilled twice in Oro No. 2, a major reverse fault causing repetition of the entire Catatumbo formation. A columnar section of the Catatumbo formation in Oro No. 3 is shown in Figure 6.

LITHOLOGY: The formation is predominantly composed of dark-gray shales and claystones, commonly somewhat carbonaceous and containing small nodules and thin

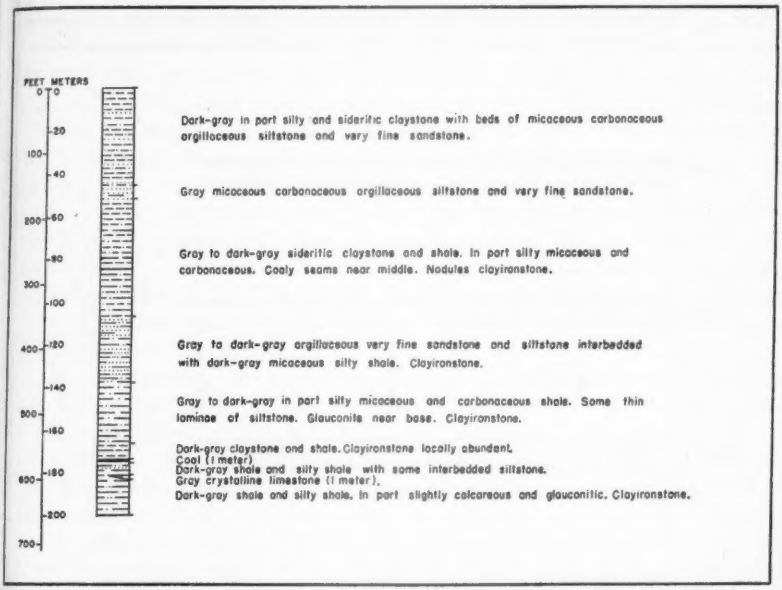

FEET METERS
0 0
20
100 40
60
200 80
300 100
120
400 140
500 160
180
600 200
700
Dark-gray in part silty and sideritic claystone with beds of micaceous carbonaceous argillaceous siltstone and very fine sandstone.
Gray micaceous carbonaceous argillaceous siltstone and very fine sandstone.
Gray to dark-gray sideritic claystone and shale. In part silty micaceous and carbonaceous. Coaly seams near middle. Nodules clayironstone.
Gray to dark-gray argillaceous very fine sandstone and siltstone interbedded with dark-gray micaceous silty shale. Clayironstone.
Gray to dark-gray in part silty micaceous and carbonaceous shale. Some thin laminae of siltstone. Glauconite near base. Clayironstone.
Dark-gray claystone and shale. Clayironstone locally abundant.
Coal (1 meter)
Dark-gray shale and silty shale with some interbedded siltstone.
Gray crystalline limestone (1 meter).
Dark-gray shale and silty shale, in part slightly calcareous and glauconitic. Clayironstone.

FIGURE 6.—*Columnar section of Catatumbo formation in Oro No. 3 well*

lenses of brown clay-ironstone. In the Río de Oro area there is a considerable amount of interbedded and interlaminated gray and dark-gray argillaceous very fine- to fine-grained sandstone, the beds ranging from 0.5 to 10 meters in thickness. Micaceous-carbonaceous laminae are common. Farther south, sandstones are much less common (Fig. 7), and some well sections contain practically none. The percentage of claystones, characteristically containing more or less abundant siderite spherules normally less than 1 millimeter in diameter, decreases from northwest to southeast, and the claystones are replaced by silty and sandy dark-gray shales. The formation commonly contains a few thin beds of coal, particularly in its lower part. Sandy sediments of the lower-most portion contain glauconite and rarely a few thin beds of nonglauconitic limestone. The associated shales are sparsely fossiliferous, containing arenaceous Foraminifera, ostracods, and some large fossils.

THICKNESS: The formation shows a considerable range in thickness. Well sections range from 106 to 208 meters in thickness; the thinner sections were logged on the Tibú and Sardinata anticlines (Fig. 7). Surface sections measured on and adjacent to the Concession show 245 to 270 meters for the formation. It is at least 300 meters

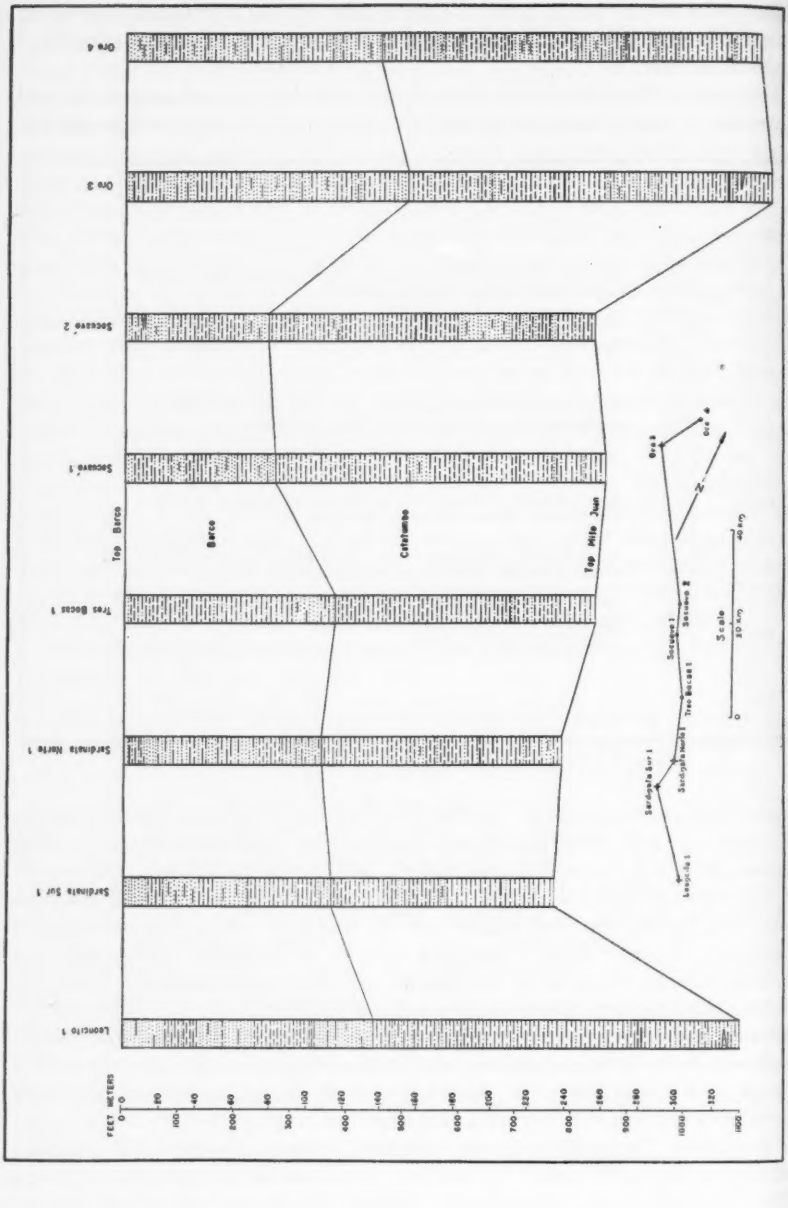


FIGURE 7.—*Chart showing lateral variations of Barco and Catatumbo formations*

thick on the Río Pamplonita near Donjuana, south of the Concession, where the base of the formation is covered.

PRODUCTIVE CHARACTER: Production is obtained from sandstones in the Catatumbo on the Río de Oro and Sardinata anticlines, and many lenses and beds of sandstone show oil staining. In the Río de Oro field, where the main production is obtained from the Catatumbo formation, the sandstones commonly have permeabilities of less than 10 millidarcys and have an average porosity of 6.7 per cent.

Minor amounts of thin brown highly bituminous shales have been noted locally in the Catatumbo, and the oil may be indigenous. However, the possibility that it may have reached these sands by migration from a deeper source must be recognized. The Río de Oro anticline is faulted and offers possibilities of upward migration from the underlying Cretaceous, but the Sardinata anticline offers less possibility of vertical migration, yet shows some oil of similar character.

BOUNDARIES AND RELATIONSHIPS: The lower boundary of the Catatumbo formation is at the top of the glauconitic limestone facies of the Mito Juan formation. The upper boundary is drawn at the base of the fairly continuous section of sandstones which constitute the Barco formation. Both boundaries are apparently conformable.

HEAVY MINERALS: The Catatumbo sandstones show a well-developed garnet-chloritoid suite of minerals.

AGE AND ORIGIN: The age of the Catatumbo has not been definitely established, but there is good reason to think it may be Upper Cretaceous, and it is being tentatively so classified. A sample of fossiliferous arenaceous shale, collected from the Catatumbo in the Puerto Salado area, was submitted to A. A. Olsson, who identified (personal communication) *Venericardia* sp., *Mytilus* or *Modiolus*, *Calyptraea* sp., *Ostrea*, possible young of a species of *Exogyra*, shell prisms (rare) of a species possibly *Inoceramus*, and echinoid plates and spines, the latter being very similar to spines found in a sample from the Río de Oro limestone facies of the Mito Juan formation. Concerning this marine fauna of the Catatumbo, Olsson states that without evidence to the contrary he would be inclined to regard it as Upper Cretaceous. Hedberg (personal communication) states that in his opinion the fact that the *Ammobaculites colombianus* zone extends up from the Mito Juan into the lower part of the Catatumbo is further evidence that the Catatumbo is uppermost Cretaceous.

Except for its lower part, which is included in the *Ammobaculites colombianus* zone, the shales of the Catatumbo are characteristically barren of Foraminifera. Presumably much of the formation was laid down under brackish-water or nonmarine conditions.

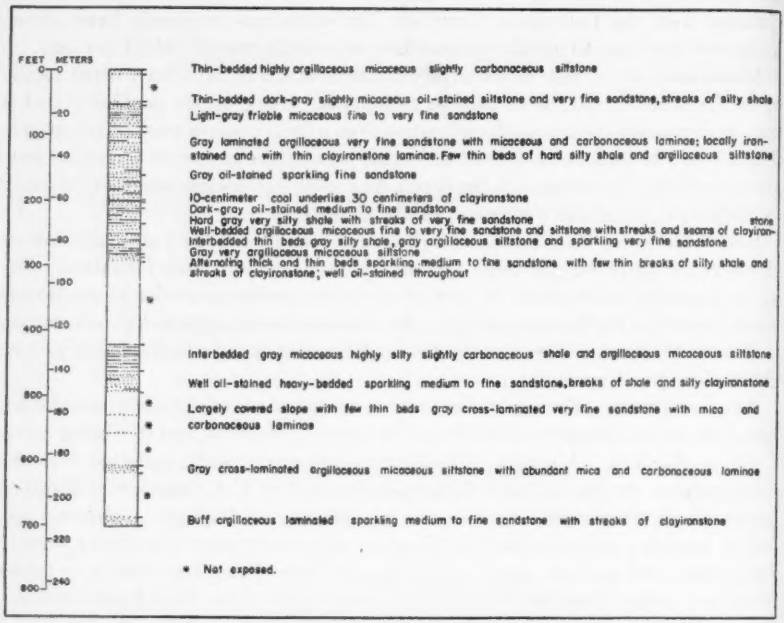
CORRELATION: The formation correlates directly with the lower part of the Third Coal horizon of western Venezuela and with some of the uppermost Mito Juan as the top of that formation is, at least locally, drawn in western Venezuela. It is probably equivalent to the upper part of the Umir and possibly some of the lowermost Lisama of the Magadalena valley.

OCCURRENCE: The formation crops out in the southern half and along the western side of the Concession.

FIGURE 7.—*Chart showing lateral variations of Barco and Catatumbo formations*

TERTIARY SYSTEM

Barco formation (lower Eocene).—The Barco formation is named from the East Barco Ridge, a prominent escarpment formed by resistant sandstones of this formation along the east flank of the Petrolea anticline. Although exposures are fairly


FEET METERS
0 0
100 20
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300 100
400 120
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500 160
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600 200
700 220
240
800
Thin-bedded highly argillaceous micaceous slightly carbonaceous siltstone
Thin-bedded dark-gray slightly micaceous oil-stained siltstone and very fine sandstone, streaks of silty shale
Light-gray friable micaceous fine to very fine sandstone
Gray laminated argillaceous very fine sandstone with micaceous and carbonaceous laminae; locally iron-stained and with thin clayironstone laminae. Few thin beds of hard silty shale and argillaceous siltstone
Gray oil-stained sparkling fine sandstone
10-centimeter coal underlies 30 centimeters of clayironstone
Dark-gray oil-stained medium to fine sandstone
Hard gray very silty shale with streaks of very fine sandstone
stone
Well-bedded argillaceous micaceous fine to very fine sandstone and siltstone with streaks and seams of clayiron-
Interbedded thin beds gray silty shale, gray argillaceous siltstone and sparkling very fine sandstone
Gray very argillaceous micaceous siltstone
Alternating thick and thin beds sparkling medium to fine sandstone with few thin breaks of silty shale and streaks of clayironstone; well oil-stained throughout
Interbedded gray micaceous highly silty slightly carbonaceous shale and argillaceous micaceous siltstone
Well oil-stained heavy-bedded sparkling medium to fine sandstone, breaks of shale and silty clayironstone
Largely covered slope with few thin beds gray cross-laminated very fine sandstone with mica and carbonaceous laminae
Gray cross-laminated argillaceous micaceous siltstone with abundant mica and carbonaceous laminae
Buff argillaceous laminated sparkling medium to fine sandstone with streaks of clayironstone
* Not exposed.

FIGURE 8.—*Type section of Barco formation from East Barco Ridge*

continuous along the ridge, a section measured at any point must be somewhat incomplete. However, the general composition of the formation is very well known from a large number of surface and well sections. As a type section, one measured on the East Barco Ridge 3 kilometers south of the Barco Venezuela triangulation station is presented (Fig. 8). Though incomplete it is the best available section from the type locality.

LITHOLOGY: The formation consists of a series of interbedded sandstones, shales, and claystones. It is topographically important, forming prominent strike ridges. The sandstones occur in beds ranging in thickness from 0.3 to 20 meters, are in large part gray argillaceous very fine- to medium-grained well-sorted cross-bedded and cross-laminated, and locally contain abundant micaceous-carbonaceous partings and numerous shale laminae. Some siltstones and rarely coarse-grained sandstones have been noted. A distinct type of sandstone, which is everywhere found in the Barco formation and forms a fair proportion of the sandstone content, is the so-called "sparkling sandstone." Sandstones of this type are more common in the middle and

lower parts of the formation and are relatively clean fine- to medium-grained sandstones in which secondary growth of the sand grains has formed myriads of crystal faces. These faces sparkle in the sun, hence the name.

Interbedded with the sandstones are shales and claystones, commonly gray or dark-gray, in part silty, micaceous, and carbonaceous, and locally rich in minute siderite spherules. Brown clay-ironstone in the form of thin lenticular masses and small nodules is common. Some coal, in one or more thin beds, is generally present in the upper part of the formation. The shales and claystones normally form one-third to half the total thickness of the formation. Locally they may form about three-fourths of the thickness, and in three wells which drilled the Barco on the Tibú anticline shales and claystones form four-fifths to eight-ninths of the formation. However, these extreme cases are not at all typical.

THICKNESS: The formation ranges from 150 to 278 meters in thickness in 12 typical outcrop sections on and close to the Concession, the average being 194 meters. In wells the formation ranges from 76 to 198 meters in thickness with an average of 130 meters. Wells on the Sardinata, Tibú, and Socuavó anticlines show thin sections (Fig. 7), bringing down the average thickness. It is probably significant that these wells are on the crestal portions of the anticlines, whereas the majority of surface sections have been measured on flanks of folds. Well evidence alone has suggested that a down-flank increase of sandstone exists on at least some folds. Regionally the Barco thins to the northeast.

PRODUCTIVE CHARACTER: Production is obtained from the Barco sandstones on the east flank of the Petrolea anticline (Carbonera fault zone) and in the Tibú-Socuavó area. Sandstones in the formation commonly show oil staining or bituminous residue. The formation carries gas on the Sardinata anticline. In the Río de Oro field the sandstones are exposed but carry some heavy inspissated oil.

Production is obtained mainly from the "sparkling sandstones." An average porosity of 12.5 per cent and average permeability of 79 millidarcys was obtained from 92 core samples of Barco sandstone from 14 wells. The "sparkling sandstones" are thought to yield production largely by intergranular flow, fractures playing a secondary role.

Oil found in the Barco formation is somewhat heavier than that in the Catatumbo formation but is similar in its dark-brown to black color. It is probably indigenous to the formation, but the possibility of a deeper origin has not been disproved.

BOUNDARIES AND RELATIONSHIPS: The base of the Barco formation is drawn where the light-colored sandstones of the formation give way to the dark sandy shales of the Catatumbo formation. The contact is apparently conformable and is generally distinct. The top of the formation is drawn at the first fairly prominent sandstone below the coal series of the basal Los Cuervos formation, and the contact is apparently conformable. This is not as readily recognized as the base of the Barco but may usually be identified without much difficulty in all but those few sections (wells on the Tibú and Socuavó anticlines) where the upper Barco sandstones have been largely replaced by shales.

HEAVY MINERALS: A weak garnet-chloritoid suite, with garnet very scarce, is characteristic of heavy-mineral assemblages of sandstones in this formation.

AGE AND ORIGIN: The age of the Barco formation has not been definitely established. It is essentially barren of fossils and probably is largely of nonmarine origin. It is tentatively assigned to the lower Eocene.

CORRELATION: The Barco correlates directly with the major part of the Tabla sands of the Third Coal horizon of western Venezuela. It probably correlates with the lower part of the Lisama formation of the Magdalena valley.

OCCURRENCE: The formation crops out in the southern half and along the west side of the Concession. It is a recognizable unit throughout the Concession and adjacent areas.

Los Cuervos formation (lower Eocene).—The Los Cuervos formation is named from Quebrada Los Cuervos, a tributary of the Río Catatumbo above Puerto Barco, and the type section is in the same stream. However, the formation is better known from sections measured farther north on the Río de Oro anticline. A composite section from exposures approximately 15 kilometers north of the type section is shown and described in Figure 9.

LITHOLOGY: The formation is composed mainly of claystones and shales, with coal beds in its lower part and some sandstone beds throughout. The lower 75 meters consists of dark-gray carbonaceous shales and claystones interbedded with micaceous-carbonaceous siltstones, fine-grained sandstones, and coals. Rarely thin limestones showing cone-in-cone structure have been noted. The coal beds are commonly 8 to 10 in number and range in thickness from 0.1 to 2.5 meters. The usual thickness is 0.5 to 1 meter. The coals are lignitic to bituminous; the fixed carbon ratio in 22 samples ranges from 49.0 to 58.4 and averages 54.5. They constitute the major coal resource of the region.

Above the coal series the Los Cuervos is made up of gray and greenish-gray in part silty and commonly sideritic claystones, the siderite occurring as spherules generally less than 1 millimeter in diameter. There are some greenish-gray argillaceous sandstones, commonly in beds less than 6 meters thick. In the lower part of the claystone sequence there is considerable shale, generally dark gray and carbonaceous, and the claystones are only slightly mottled. However, the overlying claystones, which compose the bulk of the division, are characterized by locally abundant red, yellow, and purple mottling. The thin but hard sandstones of the Los Cuervos at many places form strike ridges.

THICKNESS: In 16 measured surface sections the formation ranges in thickness from a minimum of 245 meters in the northwestern part of the Esperanza dome to a maximum of approximately 490 meters on the Río de Oro anticline near Puerto Barco. Along the west side of the Concession it appears to thicken both to the north and south of the thinner sections on the Esperanza dome. Well sections range from a minimum of 249 meters in Carbonera No. 1 to a maximum of 426 meters in an incomplete section in Oro No. 3, which began drilling a little below the top of the formation. Thicknesses ranging from 282 to 316 meters were logged on the Sardinata, Tibú, and Socuavó anticlines. The well sections show a northward thickening.

PRODUCTIVE CHARACTER: Production is obtained from two argillaceous sandstones in the upper part of the formation in Carbonera No. 2, but this is the only production

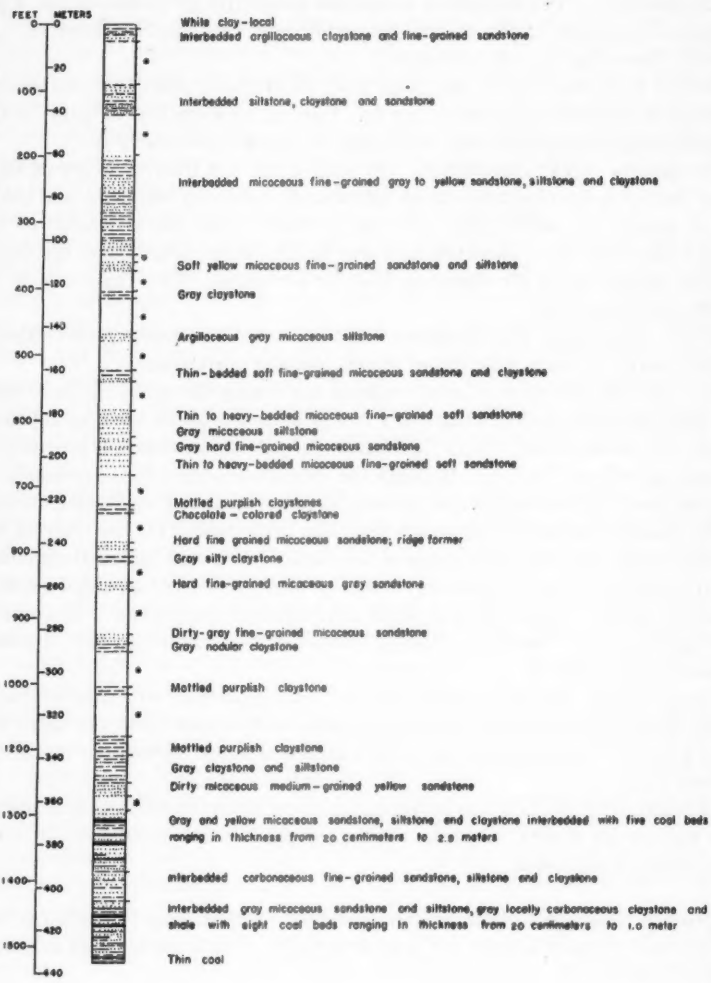

FEET
METERS
White clay-local
Interbedded argillaceous claystone and fine-grained sandstone
Interbedded siltstone, claystone and sandstone
Interbedded micaceous fine-grained gray to yellow sandstone, siltstone and claystone
Soft yellow micaceous fine-grained sandstone and siltstone
Gray claystone
Argillaceous gray micaceous siltstone
Thin-bedded soft fine-grained micaceous sandstone and claystone
Thin to heavy-bedded micaceous fine-grained soft sandstone
Gray micaceous siltstone
Gray hard fine-grained micaceous sandstone
Thin to heavy-bedded micaceous fine-grained soft sandstone
Mottled purplish claystones
Chocolate-colored claystone
Hard fine grained micaceous sandstone; ridge former
Gray silty claystone
Hard fine-grained micaceous gray sandstone
Dirty-gray fine-grained micaceous sandstone
Gray nodular claystone
Mottled purplish claystone
Mottled purplish claystone
Gray claystone and siltstone
Dirty micaceous medium-grained yellow sandstone
Gray and yellow micaceous sandstone, siltstone and claystone interbedded with five coal beds ranging in thickness from 20 centimeters to 2.8 meters
Interbedded carbonaceous fine-grained sandstone, siltstone and claystone
Interbedded gray micaceous sandstone and siltstone, gray locally carbonaceous claystone and shale with eight coal beds ranging in thickness from 20 centimeters to 1.0 meter
Thin coal
• Not exposed.

FIGURE 9.—*Composite section of Los Cuervos formation on the Río de Oro anticline*

from the Los Cuervos on the Concession. The formational equivalent in the Tarra field of Venezuela is productive. Dark-brown to black oil staining, with more or less free oil, is found locally in sandstones and in fractures in claystones and shales in the formation. Two samples of sandstones productive in Carbonera No. 2 show porosities of 15.5 and 7.5 per cent and permeabilities of less than 10 millidarcys. Presumably fracturing controls production.

Both at Carbonera and in the Tarra field, faulting may have been important in allowing oil migration from lower sources. Only in the lower Los Cuervos are there sediments approaching the usual conception of petroleum source beds.

BOUNDARIES AND RELATIONSHIPS: The base of the Los Cuervos is drawn on top of the first fairly prominent sandstone immediately below the coal series, and the contact is apparently conformable. The top is drawn where the claystones or argillaceous siltstones of the formation give way to the distinctively cleaner and coarser-grained sandstones of the overlying Mirador formation. This contact is at least locally unconformable.

HEAVY MINERALS: The formation contains a well-developed garnet-chloritoid suite of heavy minerals, with etched garnet common to abundant.

AGE AND ORIGIN: No conclusive evidence concerning the age of the Los Cuervos has been obtained, the formation being largely barren of fossils other than plant remains, but the equivalent Third Coal horizon of western Venezuela is generally considered to be lower Eocene. Although the formation is thought to be mainly nonmarine, there was some salt water invasion when the basal beds were being deposited. A thin fossiliferous black shale occurs very close to the base of the Los Cuervos in the Puerto Salado area, and in a sample of this shale A. A. Olsson (personal communication) recognized what was probably a species of *Diplodonta* or an allied genus, the possible presence of a species of *Anomia*, and fragments of an oyster. He considered the fauna to be of "marine to slightly brackish-water" origin and that it could be Cretaceous or Tertiary.

CORRELATION: The Los Cuervos may be correlated directly with most of that part of the Third Coal horizon of western Venezuela which occurs above the Tabla sands. It is probably represented in part of the Lisama and Toro formations of the Magdalena valley.

OCCURRENCE: The Los Cuervos formation crops out in the southern half and along the western side of the Concession. It is a recognizable unit throughout the Concession and adjacent areas.

Mirador formation (middle or upper Eocene?)—The Mirador formation is named from Cerro Mirador, District of Colón, Venezuela. The name has been in use for at least 25 years.

LITHOLOGY: The Mirador formation is predominantly composed of sandstones. These are pale buff to white, characteristically clean, massive, moderately hard to friable, fine-to coarse-grained, and in part conglomeratic. It contains some thin beds of gray and brownish-gray micaceous shale. An interval of shale and sandy shale with a little sandstone commonly occurs 40 to 75 meters below the top of the formation and ranges from 10 to 70 meters in thickness. The sandstones in the lower part

of the formation tend to be more thinly bedded and less clean than the bulk of the formation. The Mirador is topographically prominant, forming escarpments, ridges, cliffs, and prominent dip slopes.

THICKNESS: The formation ranges from 160 to 400 meters in thickness in surface sections, and in these no regional trend is discernible. Well sections show 251 and 256 meters on the Sardinata anticline, 323, 342, and 347 meters on the Tibú anticline, and 370 and 448 meters on the Socuavó anticline. The well sections indicate a westward and northward thickening. In the Río de Oro area the Mirador cannot be divided with certainty from the overlying Carbonera formation, but the combined thickness of the two formations appears greater there than farther south. As a whole, the Mirador is thicker on the Concession than the 244 to 259 meters cited by Liddle (1928, p. 195) for the formation on the Tarra anticline.

PRODUCTIVE CHARACTER: No production is obtained from the formation on the Concession. Some seepages of heavy oil have been found on outcrops, but a stratigraphically lower source for this oil is probable. A little staining has been rarely noted in well sections. However, the Mirador is an important producing formation on the faulted Tarra anticline. On the Concession the Mirador is the source of many springs of fresh water, some of them hot (65° C. in Quebrada Agua Caliente on the east flank of the Petrolea anticline), and wells have encountered hot fresh water in the formation. Deep and rather rapid circulation is presumably the source of the water's heat.

BOUNDARIES AND RELATIONSHIPS: The base of the Mirador is drawn where the sandstones of the formation rest on the claystones or siltstones of the Los Cuervos. The contact is easily recognized and is at least locally unconformable. In Quebrada Agua Caliente an angular unconformity is evident between the Mirador and the Los Cuervos. Unevenness on this contact has also been noted on the González anticline. Regularity in thickness of the Los Cuervos on the Sardinata, Tibú, and Socuavó anticlines would suggest no more than a minor unconformity at the base of the Mirador, but a considerable time hiatus in an area of low relief could be postulated.

The Mirador-Los Cuervos contact represents a major change in sedimentation for the region, as it marks the first appearance above the Uribante of abundant coarse clean sandstones. Clay-size sediments compose most of the section between the Uribante and the Mirador. Some minor diastrophic movements in areas receiving sediments might be expected to accompany profound changes in source areas, so some unconformity between the Mirador and the Los Cuervos would be logical.

The top of the Mirador is drawn where the clean sandstones give way to gray micaceous in part sandy shales which form the lower part of the overlying Carbonera formation. Some suggestion of unconformable relations between the Mirador and the overlying Carbonera formation (Sandy Shale horizon) has been reported from Venezuela (Liddle, 1928, p. 281). A wide range in thickness has been noted for the formation on the Concession, and unconformable relations may be indicated at the top as well as at the base.

In the Río de Oro area distinction between the Mirador and the overlying Carbonera formation is very difficult, and the top of the Mirador could not be drawn with certainty. That area is characterized by more sandstones in the section above defi-

nite Mirador and also a thickening of the combined Mirador-Carbonera formations. In wells on the Sardinata, Tibú, and Socuavó anticlines, where complete sections of the Mirador are available, the top is readily recognized and is drawn at the base of the shale interval which forms the basal part of the Carbonera formation. The top of the Mirador is generally recognizable in the surface sections south of the Río de Oro area.

Approximately 50 meters above the top of the Mirador, in the basal shales of the Carbonera formation, a cannel coal can be correlated with a subasphaltic coal (Liddle, 1928, p. 283) in the equivalent part of the Sandy Shale horizon in the District of Colón, Venezuela. Recognition of this coal strengthens belief that the Mirador as defined on the Concession is identical with the Mirador of Venezuela.

HEAVY MINERALS: The formation is characterized by a very simple mineral suite in which etched garnet and chloritoid, generally characteristic of the Eocene sandstones of Venezuela and Colombia, are very rare or absent.

AGE AND ORIGIN: Direct evidence concerning the age of the Mirador has not been obtained; no fossils have been found in the formation. On the basis of its stratigraphic position a middle to upper Eocene age has generally been assigned; upper Eocene seems more probable. It is nonmarine.

CORRELATION: The Mirador as known on the Concession may be correlated directly with the Mirador of western Venezuela. It is probably equivalent to the La Paz sandstones of the lower part of the Chorro series of the Magdalena valley.

OCCURRENCE: The Mirador crops out in the southern half and western part of the Concession and in adjacent parts of Colombia and Venezuela. It is probably of continuous subsurface extent over a considerable area in the southwestern part of the Maracaibo basin.

Carbonera formation (*upper Eocene?—Oligocene*).—The Carbonera formation is named from Quebrada Carbonera, a tributary of the Río Zulia on the east flank of the Petrolea anticline, where the formation is well exposed. The type section (Fig. 10) is also in this stream, approximately 12 kilometers northwest of Puerto Villamizar on the Río Zulia.

LITHOLOGY: The formation consists of a thick series of claystones and various amounts of associated sandstones; some lignitic coals occur in its upper and lower parts. The claystones, normally the major constituent, are mostly gray with some greenish-gray and brown intervals. Red and yellow mottling is common, and siderite, both in small spherules and irregular masses a few centimeters in size, is fairly abundant. There are some dark-gray micaceous in part silty shales, particularly in the top and bottom 50 to 100 meters.

The sandstones are generally in beds 5 to 10 meters thick but range up to 30 meters in thickness, and beds less than a meter thick are not uncommon. They are gray and greenish gray, and most range from fine- to coarse-grained, but there is also a considerable amount of very fine-grained micaceous sandstone. Well sections show about 25 meters of sandstone 125 to 185 meters below the top of the formation, and sandstones are particularly well developed in the lower 125 to 250 meters of the for-

FEET
METERS
Buff friable argillaceous very fine sandstone with interlaminated siltstone
Brown, gray and buff argillaceous micaceous friable very fine sandstone
Interbedded thin beds of buff argillaceous slightly micaceous very fine sandstone and argillaceous siltstone
Alternating thick and thin beds friable fine sandstone
Gray micaceous silty foraminiferal shale
Soft gray claystone
Gray very argillaceous very fine sandstone
Brown very silty claystone
Mottled silty shale
Mottled claystone
25 centimeter bed bright coal
Soft gray slightly silty claystone
Thinly bedded fine sandstone with thinner beds of shale
Greenish-gray slightly calcareous argillaceous micaceous siltstone with thin beds of bright coal, carbonaceous shale and lignite
Dark-gray micaceous slightly carbonaceous and pyritic very silty shale with thin beds argillaceous very fine sandstone and siltstone. Foraminiferal
Hard gray very fine sandstone with abundant carbonaceous stringers
Interbedded gray and dark-gray soft claystone and dark-gray silty micaceous nodular carbonaceous shale with lenses of clayironstone. Thin bed of coal near top
Interbedded thin beds of brown-gray argillaceous siltstone and gray silty shale
Mottled silty claystone
Light-gray and purple mottled micaceous silty claystone
Gray very fine sandstone
Gray slightly micaceous and pyritic claystone
Interbedded brown slightly micaceous siltstone and very fine to fine sandstone with thin bed of clayironstone at top
Purple and gray mottled slightly calcareous very silty claystone
Greenish-gray very argillaceous micaceous slightly calcareous and chloritic siltstone
Greenish-gray heavy-bedded very argillaceous micaceous very fine sandstone with lenses of gray friable very fine sandstone
Buff cross-bedded friable medium to fine sandstone with interbedded brown and greenish-gray argillaceous micaceous siltstone
Greenish-gray heavy-bedded argillaceous micaceous siltstone, grading into well-bedded laminated siltstone with abundant mica in laminae
Gray slightly micaceous and silty sparsely foraminiferal nodular shale
Gray friable massive very fine sandstone
Gray cross-bedded argillaceous fine sandstone
Greenish-gray slightly chloritic micaceous silty shale, locally concretionary
Hard-gray very fine sandstone with thin gray silty shale breaks
Light-grey and purple mottled micaceous silty claystone with thin beds and laminae of black carbonaceous shale and bright coal
Dark-grey and brown silty foraminiferal shale with a thin bed of coal
Interbedded brown argillaceous micaceous siltstone and grey silty shale with a thin bed of coal
Pink medium to fine sandstone
* Not exposed

FIGURE 10.—*Type section of Carbonera formation from Quebrada Carbonera*

mation. However, the bottom 10 to 75 meters consists mainly of shales. The sandstones are characteristically more argillaceous than those of the Mirador.

Some thin beds of lignitic and cannel coals and carbonaceous shales occur in the top and bottom 100 meters of the formation; analyses of 10 coal samples show fixed carbon ratios ranging from 30.2 to 46.6 and averaging 39.7. Scarce thin limestones have also been found in the same intervals. Approximately 100 meters below the top of the formation on the Tibú anticline, remains of a few small mullusks were found in a highly carbonaceous shale about 5 meters above a 2-meter interval of glauconitic very argillaceous siltstone. Cuttings from Socuavó No. 2 showed some glauconitic sandstone about 60 meters above the base of the formation. On the Tibú and Socuavó anticlines the extreme top of the formation is glauconitic. The glauconite indicates stages of marine to brackish-water invasion.

THICKNESS: Surface measurements in the southern part of the Concession usually show about 500 meters for the Carbonera; 410 meters was measured on the Leoncito anticline, and an abnormal thickness of 720 meters was measured on the Río Nuevo west of Sardinata No. 1. Wells show 461 and 475 meters on the Sardinata anticline, 479 and 500 on the Tibú anticline, and 560 meters on the Socuavó anticline. The wells show a westward and northward thickening, accompanied by an increase in the percentage of sandstones. As previously stated, separation of the Carbonera and Mirador formations is very difficult in the Río de Oro area, where the combined thickness of the two formations is about 1220 meters.

PRODUCTIVE CHARACTER: Much dark-brown oil staining was found in sandstones in the upper part of the formation in wells on the Tibú anticline and to a lesser extent on the Socuavó anticline. The stained sandstones occur 140 to 183 meters below the top, range from fine- to coarse-grained, and are rather clean. Although some residual free oil and a little gas are still present, the sandstones carry fresh water in common with the other sandstones in the formation. A few small seepages of dark-brown oil occur on the outcrop of the formation on the Tibú anticline. A former oil accumulation has probably been flushed. In the faulted Tarra field important production is obtained from sandstones in this formation, especially the Cubo sands.

Source of the oil found in the upper Carbonera sandstones on the Tibú and Socuavó anticlines is unknown. Faulting, which might be important in permitting vertical migration from deeper sources, is as yet undetermined. Also, the entirely oil-free sandstones lower in the formation indicate that oil did not reach its present position in the upper sandstones by migration from below. The oil is probably indigenous to the formation.

BOUNDARIES AND RELATIONSHIPS: The base of the Carbonera formation is drawn where the shales in its base are in contact with the massive clean coarse sandstones of the Mirador. As mentioned, the wide range in thickness of the Mirador formation has suggested the possibility that this contact may be unconformable. In the Río de Oro area the base of the formation is not definitely recognizable. The top is drawn where the thin sandstones and sandy shales of the formation give way to the almost pure shales of the overlying León shale formation. The upper contact is apparently conformable.

HEAVY MINERALS: The Carbonera formation carries a garnet-chloritoid suite of

heavy minerals with etched garnet fairly common, chloritoid usually present, and staurolite rarely present. Epidote is common in the Río de Oro area but has not been found elsewhere on the Concession.

AGE AND ORIGIN: Opinions vary as to whether the Carbonera formation is upper Eocene or Oligocene. The formation is considered to be largely nonmarine in origin as indicated by coals at top and base, by the abundance of poorly bedded mottled claystones, and by the rarity of fossil remains, but nevertheless the formation contains some marine beds. Six large collections of Carbonera fossils were made by H. S. Ladd, one from the type section in Quebrada Carbonera and five in the area north of Cúcuta, between El Cerrito and Agua Blanca. He considered the Carbonera to be upper Eocene. During 1942 an excellent collection of fossil material from the El Cerrito locality 7 kilometers northeast of Cúcuta was made by Mr. R. B. Wheeler of the Texas Petroleum Company. It was submitted to A. A. Olsson, who has reported as follows:

"CÚCUTA AREA:

[*Plates 4 and 5*] illustrate some of the principal species from the collections made by Mr. R. B. Wheeler in the Cúcuta area. Although this fauna with *Hannatoma* and *Pseudofaunus* has been known near Cúcuta for many years, these collections have added several species and it is by far the most marine assemblage so far known from these beds.

Coll. 42-RW-3. This sample has the following species:

Hannatoma n. sp. [*Pl. 4, figs. 1–3.*]
I have previously identified this species with *Hannatoma gesteri* Hanna and Israelsky, originally described from the Punta Bravo grits of Perú (also known from the Mururucú district of the San Jorge, Colombia) but more material since available indicates that the Cúcuta form is probably a distinct species, differing by its stronger spiral cords, especially the superior one situated next the suture.

Cerithium n. sp.
This is a large gasteropod with smooth spire-whorls, later becoming ribbed. It is probably a new genus but closer determination will have to await more material.

Harrisianella cf. *peruviana* Olsson [*Pl. 4, fig. 5.*]
In Perú, this species seems to be limited to the Eocene.

Turritella aff. *chira* Olsson [*Pl. 4, fig. 4.*]
The only *Turritella* as yet known from the Cúcuta beds is a species belonging to the general group of *Turritella chira* Olsson from Perú. It differs however from the typical species by its more rounded whorls and simpler sculpture. *Turritella chira* in Perú ranges from the Upper Eocene into the Oligocene.

Melongena n. sp. sp. 1 [*Pl. 4, fig. 6.*]
This species is quite common and evidently distinctive.

Cymia cf. *berryi* Olsson
This is a large shell with remains of strong shoulder spines. It is probably correctly referred to this Peruvian species but the columellar area is concealed so the presence of columellar folds cannot be verified.

Polinices n. sp. [*Pl. 4, fig. 9.*]

Anomia n. sp. [*Pl. 5, figs. 1, 2.*]
See remarks under other sample.

Rhaetomya sp. [*Pl. 5, fig. 3.*]
The genus *Rhaetomya* or *Amotapus* is generally considered as Eocene but a number of Oligocene occurrences are known. In Perú, this genus ranges from the Upper Middle Eocene (Parinas ss.)

well up into the Middle Oligocene (Punta Bravo grits). Only two species have been named from South America but there are possibly others.

Ostrea sp.

Pitar sp. [*Pl. 4, fig. 10.*]
At least two species are present belonging to this genus.

Clementia peruviana Olsson
This species is represented by fragments only.

Mactra sp. [*Pl. 5, fig. 4.*]

Tellina sp.

Phacoides sp.

Coll. 42-RW-4. This sample has the following species:

Polinices (*Neverita*) cf. *subreclusiana* Olsson [*Pl. 4, fig. 8.*]

Polinices sp. [*Pl. 4, fig. 9.*]

Turritella aff. *chira* Olsson [*Pl. 4, fig. 4.*]

See remarks under preceding sample.

Cerithiella or *Cerithiopsis* sp. [*Pl. 5, fig. 5.*]

Hannatoma n. sp. [*Pl. 4, figs. 1–3.*]
Only a single young specimen in this sample.

Melongena n. sp. sp. 1 [*Pl. 4, fig. 6.*]
No species similar to this form is known in our Tertiary faunas.

Melongena n. sp. sp. 2 [*Pl. 4, fig. 7.*
Differs from the preceding by the absence of a basal cord. Its reference to the genus is not certain.

Harrisianella cf. *peruviana* Olsson [*Pl. 4, fig. 5.*]

Olivella sp.

Anomia n. sp. [*Pl. 5, figs. 1, 2.*]
This is an unusually large species for this group. It is referred to this genus tentatively, as the characters separating the genera of the Anomidae are internal and are not exposed in this specimen. In future collecting, examples showing the interior of the valves, particularly the muscle scars and the method of attachment either by an open or closed foramen or byssal hole as well as fragments of the shell with the surface sculpture should be looked for. The fossil is apparently common and characteristic of this level.

Arca (*Arginella*) cf. *puntabravoensis* Olsson and cf. *ovalis* McNeil [*Pl. 5, fig. 6.*]
This is a group of small Arks, preeminently characteristic of the Oligocene. They are small and generally well-rounded and globose forms.

Tagelus sp.

Tellina sp.

Mactra sp. [*Pl. 5, fig. 4.*]

Pitar sp. [*Pl. 4, fig. 10.*]

Corbula sp.

Age. The occurrence of this fauna at Cúcuta is of interest because of its bearing on the age of the Mirador sandstones and Sandy Shales. In northern Perú where the *Hannatoma* fauna is so well

CARBONERA FOSSILS FROM NEAR EL CERRITO

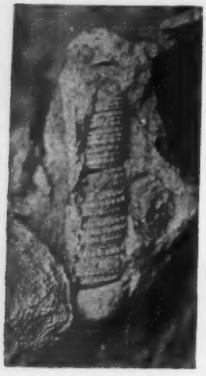
Identified and figured by A. A. Olsson

(1-3) *Hannatoma* n. sp., (4) *Turritella* aff. *chira* Olsson, (5) *Harrisianella* cf. *peruviana* Olsson, (6) *Melongena* n. sp. sp.1, (7) *Melongena* n. sp. sp.2, (8) *Polinices* (*Neverita*) cf. *subreclusiana* Olsson, (9) *Polinices* n. sp., (10) *Pitar* sp.

1

2

3



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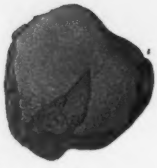

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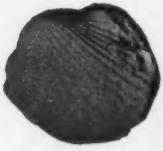


6

CARBONERA FOSSILS FROM NEAR EL CERRITO

Identified and figured by A. A. Olsson

(1-2) *Anomia* n. sp., (3) *Rhaetomya* sp., (4) *Mactra* sp., (5) *Cerithiella* or *Cerithiopsis* sp., (6) *Arca* (*Arginella*) cf. *puntabravoensis* Olsson and cf. *ovalis* McNeil

known it is characteristic of the Punta Bravo facies of the Middle Oligocene. These beds are mainly coarse, varicolored sandstones and grits, nonmarine in their lower part and unconformably resting on Eocene or overlap directly upon granite and other pre-Tertiary rocks. They are overlain by Upper Oligocene marine shales (Heath). The Hannatomas are most common in the upper part of the formation where the beds have become brackish or partially marine. *Hannatoma*, *Pseudofaunus*, and *Ampullinopsis* are also known from the Middle Oligocene of northwestern Colombia (Río San Jorge). There they occur with large, Middle Oligocene Lepidocyclinae. In Panamá, *Hannatoma* is not yet known but its associated fauna of *Pseudofaunus* and *Ampullinopsis* is known from certain Middle Oligocene beds. In this collection the presence of *Rhaetomya* and *Harrisianella* introduce an Eocene element not previously known in this fauna from Cúcuta but only the last genus is distinctly Eocene in range. In addition to the above-listed species, a few others are known from Cúcuta, amongst which may be mentioned *Pseudofaunus bravoensis* Olsson (this species is quite common opposite the power station on the river at Km. 30 on the Cúcuta-Gramalote road along with the large *Anomia*, *Ostrea*, etc.), *Ampullina bravoensis* Olsson and several large ornate forms of *Cerithium*. In my opinion, this fauna is Middle Oligocene in age."

From the above it would appear that an Oligocene age would have to be assigned to the Carbonera formation, as Olsson is classifying the El Cerrito fauna, 150 meters below the top of the formation, as middle Oligocene.

Microfossils are very rare in the Carbonera formation, but locally arenaceous and siliceous Foraminifera have been found, particularly in the uppermost part.

CORRELATION: The Carbonera formation is directly equivalent to the Sandy Shale horizon of western Venezuela and may be correlated with the Esmeraldas formation of the Department of Santander, Colombia. It may be correlated with at least part of the Chorro series and perhaps lower Mugrosa series of the Magdalena valley.

OCCURRENCE: The formation crops out widely over the Concession and is the oldest formation exposed on the Tibú and Socuavó anticlines.

León shale (upper Oligocene-lower Miocene).—The León shale formation was named by Hedberg from Quebrada León, a tributary of the Río Zulia on the east flank of the Petrolea anticline. The type section (Fig. 11) is in this same stream, about 9 kilometers northwest of Puerto Villamizar on the Río Zulia.

The formation is directly equivalent to the Upper Shales of western Venezuela, but this term is unsatisfactory.

LITHOLOGY: The León is composed almost entirely of gray and greenish-gray tough shales. There are rare thin beds of gray and buff sandstones with carbonaceous laminae, and the shales tend to become silty toward both the base and the top. In the Tibú-Socuavó area a thin series of buff sandstones and interbedded shales occurs near the middle of the formation. This series of sandstones is only locally developed and attains a maximum thickness of 28 meters. It has been called the Machete sandstone member.

THICKNESS: The León shale ranges from 510 to 785 meters in thickness on the east flank of the Petrolea anticline, and 663 meters was found on the east flank of the Leoncito anticline. In the Tibú-Socuavó area it has been estimated to be from 350 to 475 meters thick. The formation appears to thicken and become sandy in the Río de Oro area.

BOUNDARIES AND RELATIONSHIPS: The upper and lower contacts are drawn where the essentially continuous shale section of the formation gives way to sandier sediments. Both are normally distinct boundaries and appear conformable.

HEAVY MINERALS: Limited heavy-mineral data on the Machete sandstone member of the León show an assemblage different from that of either the underlying Car-

FEET
METERS
Thin-bedded gray shale
Thin-bedded gray shale
Massive bedded gray shale
Gray shale, weathers greenish-tan
Thin-bedded gray to greenish-gray shale
Massive to thin bedded gray shale
Greenish-gray massive bedded shale
Gray to greenish-gray shale
Massive gray shale, weathers greenish-gray
Gray shale, silty
Gray shale, weathers greenish-gray, and greenish-gray silty shale
Gray shale and interbedded greenish-gray silty shale
Gray to light gray shale, weathers greenish-gray
Massive gray shale to greenish-gray and thin beds of hard gray ferruginous sandstone
Massive greenish-gray silty shale
Gray shale
Gray shale with thin beds of dark fissile shale and seam of fine hard gray ferruginous sandstone
Massive gray shale
Light gray shale
Massive bedded light gray shale
Massive bedded gray shale with thin ferruginous seams and silty shale
Gray shale, weathers greenish tan
Gray fissile shale, with hard gray ferruginous seams
Gray fissile shale
Gray to light gray shale
Light gray to dark gray to black carbonaceous shale and sandy shale
• Not exposed.

FIGURE 11.—*Type section of León formation from Quebrada León*

bonera or the overlying Guayabo. Both garnet and chloritoid are absent, and the suite has been tentatively named the zircon-tourmaline-rutile suite.

AGE AND ORIGIN: The León shale has been considered as probably upper Oligocene, largely because of its stratigraphic position. The formation is poor in fossils on the Concession except for fish remains and a few noncalcareous Foraminifera. In the Río Nuevo area, five species of *Ammobaculites*, two of *Haplophragmoides*, one each of *Flabellammina*, *Spiroplectammina*, and *Quinqueloculina*, and three of *Trochammina* were recognized in the León shale and upper Carbonera formation. A relatively concentrated but still sparse occurrence of these forms was noted near the contact between the two formations, suggesting an approach to marine conditions. However, the assemblage as a whole strongly suggests a brackish-water origin for the lower León. On the basis of fossiliferous beds cropping out between Uracá and Estación Táchira, Venezuela, Kehrer (1938, p. 45–46) has classified the upper part of the Upper Shales (León) as of Miocene age. The La Cira fauna of the Magdalena valley (Wheeler, *in* Pilsbry and Olsson, 1935, p. 35) is known to occur near Cúcuta in the basal part of the immediately overlying Guayabo group. As the La Cira fauna is considered to be either upper Oligocene or lower Miocene the top of the León shale probably is not older than late Oligocene.

CORRELATION: The formation is identical with the Upper Shales of western Venezuela. Paucity of faunal data and lateral variations in lithology make regional correlations of the younger Tertiary formations very difficult. The León is probably equivalent to some part of the Mugrosa and Colorado series of the Magdalena valley. Hedberg (personal communication) expresses the opinion that it is probably equivalent to part of the El Fausto (Hedberg and Sass, 1937, p. 95–97) formation of Venezuela.

OCCURRENCE: The formation is widely exposed in the eastern half of the Concession and in adjacent parts of Colombia and Venezuela.

Guayabo group (*Miocene*).—The name of the Guayabo group is taken from Cerro Guayabo in the District of Colón, Venezuela; the name was introduced by geologists of the Carribbean Petroleum Company.

LITHOLOGY: Very little study of the Guayabo sediments has been made on the Concession, and subdivision of them has not been attempted. They consist in general of buff and light-gray friable sandstones, siltstones, and sandy shales; there are some light-gray, light-green, and mottled claystones. Lignitic coals are present in the lower Guayabo in Venezuela (Liddle, 1928, p. 336) but have not been found in outcrops on the Concession. A thin lignitic coal and carbonaceous shale was found, however, in some core holes drilled near the Río Socuavó del Norte, and the coal is in either the lower part of the Guayabo or top part of the León shale. The most complete section measured on the Concession is that in Quebrada León. From the base up it shows (1) 186 meters of buff and gray sandy shales and friable sandstones, (2) 181 meters of light-gray, light-green, and Fausto-type mottled claystones and sandy claystones, with some gray and buff sandstone, and (3) 436 meters of buff and gray friable sandstones and locally mottled claystones. The so-called Fausto type of mottling is dull red, brown, green, lavender, and purple. Apparently only equivalents of the upper El Fausto and Los Ranchos formations are represented; the La

Villa formation is not exposed. These formations are recognized in western Venezuela.

THICKNESS: The thickest section measured on the Concession is that in Quebrada León of 803 meters, but this did not extend to the top of the group. Approximately 5 kilometers southeast of Cúcuta, between Quebradas Juan Paula and Juan Frio, a section of 2640 meters of Guayabo was measured by J. W. Butler of the Texas Petroleum Company. Probably the La Villa is represented in the upper part of this section.

PRODUCTIVE CHARACTER: No production is obtained from the Guayabo group. However, a little yellow oil staining was encountered in either the lower part of the Guayabo or uppermost León shale in core holes drilled near the Río Socuavó del Norte.

BOUNDARIES AND RELATIONSHIPS: The base of the Guayabo is drawn where its sandy sediments rest in contact with the essentially pure shale of the León. The contact is apparently conformable and normally distinct. The top of the formation is not known.

HEAVY MINERALS: The Guayabo group as mapped on the Concession is characterized by a garnet-epidote-sphene suite of heavy minerals, but the suite is not distinctly developed in the lower few hundred feet of the group.

AGE AND ORIGIN: So far as known the Guayabo on the Concession is of nonmarine origin.

Fossils collected by R. B. Wheeler of the Texas Petroleum Company from the basal member of the Guayabo at a point 11 kilometers northwest of Cúcuta have been definitely assigned to the La Cira fauna by A. A. Olsson (personal communication). This would place the base in lower Miocene or upper Oligocene.

Lower, middle, and upper Miocene ages are assigned to divisions of the Guayabo in Venezuela. Presumably lower and middle Miocene are represented in the section in Quebrada León.

CORRELATION: The Guayabo group correlates directly with the same group in western Venezuela. It may be in part equivalent to the Real series of the Magdalena valley. Hedberg (personal communication) expresses the opinion that the Guayabo is equivalent to part of the El Fausto, and the Los Ranchos and La Villa formations of western Venezuela.

OCCURRENCE: The group crops out in the eastern part of the Concession and is of widespread occurrence in adjacent parts of Venezuela and Colombia.

Necesidad formation (Pliocene?—Pleistocene?).—The Necesidad formation is named from Playa Necesidad located on the Río de Oro a short distance above its confluence with the Río Catatumbo. So far as known, the name was first applied by H. F. Nash in 1919. No type section has been or can be measured as the formation is poorly exposed and its top is not known.

LITHOLOGY: At Playa Necesidad the formation consists of bright-colored red and blue clays, interbedded with coarse-grained sandstones which grade into conglomerates with pebbles up to 2 centimeters in diameter. Southeast of the Río Catatumbo the Necesidad formation as mapped consists of a thick series of fine- to coarse-grained massive cross-bedded friable buff to yellow sandstones and interbedded

claystones. These beds may not be the exact equivalent of those at Playa Necesidad. They may even belong to the upper Guayabo.

THICKNESS: At Playa Necesidad there may be as much as 50 meters of the formation. The total thickness is unknown.

BOUNDARIES AND RELATIONSHIPS: Near Río de Oro airport the formation rests horizontally against steeply dipping Guayabo.

AGE AND ORIGIN: The formation is of nonmarine origin. Its age is not known, but it is presumably Pliocene or Pleistocene. If coarse-grained sandstones and claystones which have been folded along with the Guayabo group south of the Río Catatumbo actually correlate with the Necesidad at Playa Necesidad, a Pliocene age would be more likely. However, very possibly these folded sediments should be correlated with a part of the Guayabo group.

HEAVY MINERALS: The Necesidad contains a heavy-mineral suite identical with that of the La Villa formation of western Venezuela. It has been termed the ilmenite-rutile-zircon-tourmaline suite. Garnet and epidote are very rare, which distinguishes the suite from the garnet-epidote-sphene suite characteristic of that part of the Guayabo group older than the La Villa.

CORRELATION: No correlation of the Necesidad has been attempted as its relations, even locally, are very dubious.

OCCURRENCE: The Necesidad crops out in the northeastern part of the Concession and the adjacent part of Venezuela.

RECENT DEPOSITS

No study has been made of recent sediments, but terrace deposits of gravel and sand are common, particularly along the major streams.

SURFACE INDICATIONS OF PETROLEUM

OIL AND GAS SEEPS

Oil and gas seeps are common on the Leoncito, Petrolea, and Río de Oro anticlines and are present but much less common in other parts of the Concession. Most of the seeps are found in the lower Tertiary formations, and the seepage from these, usually small in amount, consists of heavy dark-brown or black oil with little gas. In the Cretaceous along the crest of the Petrolea anticline there are numerous seeps of light, green oil usually accompanied by gas, and a similar seep occurs in Quebrada Agua Sal in the southeastern part of the Concession. The output of these seeps also is generally small, but in some instances it is or has been considerable. In the time of General Barco the oil seepage in the vicinity of the present Petrolea camp was sufficient to supply a small still, but these seeps are now relatively small. Shortly after the middle of 1940 a gathering system was installed at a seep which had recently become active at a point 1.5 kilometers south of Petrolea camp, and in the following 12 months 21,500 barrels of 40° A.P.I. oil was recovered.

ASPHALTIC DIKES

Two occurrences of asphaltic dikes are known on or near the Concession. In the trough of the syncline between the Esperanza dome and the basement-sedimentary fault contact there is an asphaltic dike ranging from 20 to 70 centimeters in thickness.

The country rock is Los Cuervos siltstone, and there is no apparent displacement of the walls. Approximately 2 kilometers south of Río Socuavó del Norte near the trough of the syncline west of the north end of the Socuavó anticline, there are several outcrops of an asphaltic dike or dikes in the Necesidad formation. The outcrops are in an almost east-west alignment and have been traced for about 700 meters. The dike appears to dip about 85° S. and has a maximum thickness of 1.5 meters.

HYDROCARBON RESIDUES

Many outcropping sandstones of the Barco and Catatumbo formations, particularly on the Leoncito, Petrolea, and Río de Oro anticlines, contain minute particles of black hydrocarbon residue partially filling the intergranular spaces. The residue is soluble in chloroform. In many outcrops it is sufficient to color the unweathered rock a gray or even dark gray.

STRUCTURE

REGIONAL

The Barco Concession lies along the southwestern edge of a northeasterly plunging lobe of the Maracaibo basin between the Sierra de Perijá on the west and the Sierra de Mérida on the southeast. This lobe of the basin is more or less bisected by a truncated anticlinorium extending from the Santiago dome, immediately north of the bifurcation of the Cordillera Oriental, northward through the Petrolea anticline and its extension in the Tarra anticline in western Venezuela. The total length of this anticlinorium is at least 120 kilometers, of which one third is on the Concession. East of the Petrolea-Tarra anticlinorium lies the Zulia syncline and to the west lies the Sardinata structural depression. The eastern margin of the Sierra de Perijá is characterized by thrusting to the east and with this there is associated a zone of folding and faulting in the eastern foothills of the range. Approximately midway between the Petrolea-Tarra anticlinorium and the above-mentioned foothills folds and just west of the axis of the Sardinata structural depression there is a north-south trend of uplift called the folds of the Sardinata depression. These structural features are shown on Plate 1.

The Petrolea-Tarra anticlinorium and the foothills uplifts are strongly expressed in the topography; the Petrolea anticline furnishes an excellent example of an anticlinal valley (Pl. 2, fig. 1). However, the folds of the Sardinata depression are in part covered by river flood plains and elsewhere are only slightly expressed in topography.

The folding represents some of the later adjustments in the Andean system. The time of major folding was post-Guayabo, hence late and post-Miocene, although some earlier folding is apparent at least locally in the unconformity between the Los Cuervos and Mirador formations of Eocene age.

PETROLEA-TARRA ANTICLINORIUM

General description.—The Santiago dome, directly south of the Concession, is a large domal uplift of semicircular outline with comparatively gentle dips toward the north, west, and south but with vertical to overturned dips along the faulted east side. Extending northward from the northeastern part of the Santiago dome is the

Petrolea-Tarra anticlinorium with a general northward plunge. Within the concession it is not a single continuous anticline but is composed of the Gonzalez, Leoncito, and Petrolea anticlines.

Gonzalez anticline.—In the southeastern part of the Concession at the south end of the Petrolea-Terra anticlinorium is the elongate north-plunging highly faulted asymmetrical Gonzalez anticline, with steep dips on both flanks. It is open to the south unless somewhat questionable transverse faulting is effective. As lowermost Eocene strata crop out on the anticline it is not a prospect for Tertiary production, and the presence of effective fault closure of the Lower Cretaceous formation is questionable.

No oil or gas seeps have been discovered, and the absence of hydrocarbon residues, common in the Barco sandstones elsewhere in the Concession, suggests that there never was an oil accumulation in the Tertiary sandstones on this structural feature. The anticline has not been tested.

Leoncito anticline.—Directly east of the Gonzalez anticline is the Leoncito anticline. It is a complexly faulted asymmetrical anticline with a steep east flank and a comparatively gentle west flank and is limited on the west by the Hortensia thrust fault. The trend is slightly east of north. The anticline plunges toward the south and is not closed on the north unless by transverse faulting. The entire Tertiary section crops out on the anticline.

There are several black oil seeps, some of which are accompanied by gas, and many outcrops of the Barco sandstones contain hydrocarbon residues. One test, Leoncito No. 1, has been drilled on the anticline. Starting in lower Los Cuervos beds it penetrated the Barco and Catatumbo formations and 215 meters into the Mito Juan formation, where the Hortensia fault was cut and the Barco formation was repeated. It was drilled almost to the base of this formation and was abandoned at a depth of 928 meters. The Lower Cretaceous was not reached. No indication of petroleum other than slightly stained sandstones was encountered. The position and elevation of the Hortensia thrust fault on the surface trace and in the well indicate that it dips 28° E.

Petrolea anticline.—Directly north of but structurally distinct from the Gonzalez anticline and en echelon to the northwest of the Leoncito anticline is the Petrolea anticline. It is a north-south trending complexly faulted closed asymmetrical anticline with steep to overturned beds on the west flank and an average dip of 15° on the east flank. On the Colombian portion of the anticline there are two local highs called the Petrolea North Dome and the Petrolea South Dome. The subsurface structure of the productive portion of the North Dome is shown in Plate 6. Taken by itself the Petrolea anticline has a closure of approximately 1000 meters and a closed area in Colombia of approximately 7000 hectares (17,300 acres). If the Petrolea and Leoncito anticlines, which have a common closure line, are taken as one structural feature, the closure is at least 1800 meters, and the closed area 18,600 hectares (48,000 acres). The entire Tertiary section up to the lower Guayabo is exposed on the flanks of the anticline. The crest of the North Dome has been eroded to within 20 meters of the La Luna formation, and that of the South Dome has been truncated to within 90 meters of the top of the Uribante formation.

There are numerous light oil and gas seeps along the crestal area of both domes.

There are also many black oil seeps and sandstones impregnated with hydrocarbon in the Eocene formations along the east flank. Exclusive of the Carbonera area, 13 wells have been drilled on the Colombian portion of the Petrolea anticline, and six productive zones have been developed in the La Luna, Cogollo, and Uribante formations.

Carbonera thrust fold.—On the east flank of the Petrolea-Tarra anticlinorium approximately 5 kilometers east of the axis of the Petrolea anticline is the Carbonera thrust fold. This structural feature is a broad nose truncated on the west by a thrust fault dipping approximately 25° E., as proved by the position and elevation of the surface trace and the points of intersection of the fault in three wells. The fault extends throughout the length of the Colombian portion of the Petrolea anticline and northward into Venezuela. Presumably the fault passes into bed slippage down dip as seismic data indicate no fault or reversal in the La Luna reflecting horizon. The oldest beds exposed east of the fault belong in the Los Cuervos formation. The Carbonera area is strictly a Tertiary prospect as there is no evidence of a structural trap in the Lower Cretaceous.

Three small producers have been completed in the Los Cuervos and Barco formations.

FOOTHILLS FOLDS

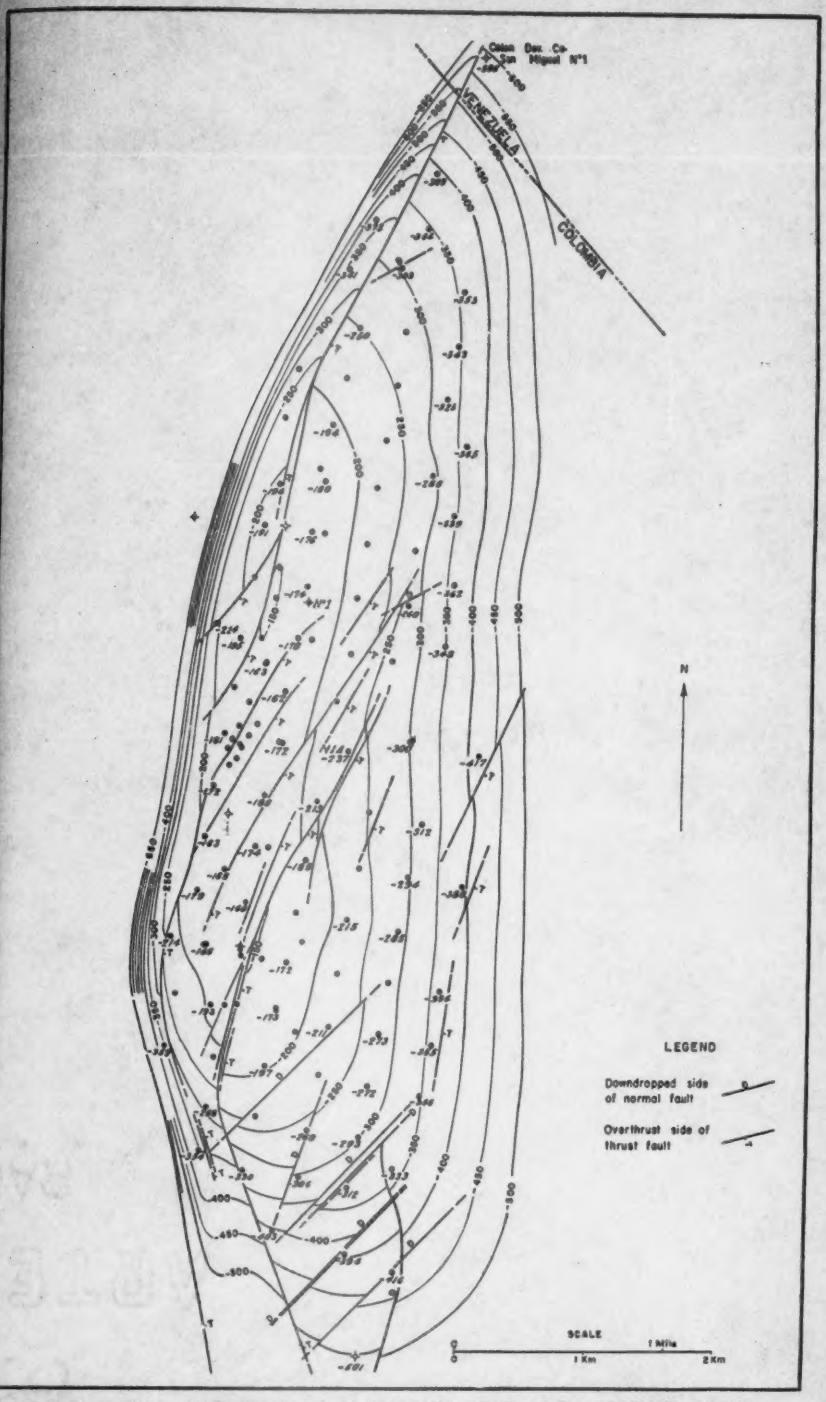
General statement.—Along the western side of the Concession is the foothill line of folding and faulting. From south to north this is composed of the Cuervo and Esperanza anticlines, the Mercedes fault zone, the Catatumbo flexure, the Río de Oro anticline, and the Confluencia dome.

Cuervo anticline.—In the southwesternmost part of the Concession plunging gently northward from the Santiago dome is the Cuervo anticline. It trends slightly east of north, and the surface crest of the anticline is cut by a thrust fault dipping 30°–35° W. There is a small amount of closure in the Tertiary of the overthrust block, but closure of the Cretaceous formations of the underthrust block is unlikely. Eocene and upper Cretaceous strata crop out on the fold.

No tests have been drilled on this anticline.

Esperanza anticline.—En echelon to the northwest of the Cuervo anticline is the Esperanza anticline, extending from the Río Sardinata northward past the Río Tibú. The portion directly east of the town of Mercedes is known as the Esperanza dome. It is a broad somewhat asymmetrical dome with comparatively gentle dips. Only minor faulting is present. A survey of the base of the Mirador formation which almost completely encircles and partly caps the dome indicates a closure of at least 300 meters and a closed area of approximately 15,000 hectares (37,000 acres). A considerable portion of the closed area is outside the Concession. As the Catatumbo formation is exposed by erosion, only the Lower Cretaceous is potentially productive. The northward pitching end of this anticline has been traced to a point north of Río Tibú, but that portion is below the closure line.

Only one very small black oil seep has been found on the anticline, and the outcropping Eocene sandstones do not show residues of former accumulation. No tests



STRUCTURAL CONTOUR MAP OF THE PETROLEA NORTH DOME

Contours on top of Zone 3. Contour interval 50 meters (164 feet). Datum sea level. Evidence for many of the minor thrust faults shown is found in the shallower horizons.

have been drilled on the Esperanza dome, chiefly because of the inaccessibility and extremely rough topography of the area.

Mercedes fault zone.—Extending along or near the basement-sedimentary contact from the town of Mercedes to and beyond the town of Sardinata is a zone of major faulting called the Mercedes fault zone. As this zone is entirely outside the Concession it has been studied only in reconnaissance. Actual exposure of the fault planes are rare, but there is obvious omission of thick sections of the sedimentary series. The fault planes seen dip steeply westward with the upthrow on the west. The total displacement of the zone must be at least 2500 meters in some areas.

Catatumbo flexure.—Little work has been done in the western part of the Concession between the latitudes of Camp Orú and Barranca Bermeja. However, numerous flights over the area and a reconnaissance survey up the Río Catatumbo to Cerro Vollee have furnished some geological data on the area. The basement sedimentary contact appears to be near the western border of the Concession. A normal sequence of Cretaceous sediments dipping about 10° E. occupies the zone between the basement contact and the Río Catatumbo. Immediately east of this river the dip rapidly increases to 50° or 60° in a narrow line of hills formed by the uptilted sandstones of the lower Tertiary. East of these hills the dip decreases rather abruptly to an average of 10°, and this dip continues to the syncline west of the Tibú and Socuavó anticlines. The zone of steep dip, named the Catatumbo flexure, extends from Camp Orú northward to the Catatumbo and on into the steep east flank of the Río de Oro anticline. Very possibly this long narrow sharp flexure may mark a thrust fault dipping west in the basement or even in the Lower Cretaceous. On the Río de Oro anticline and in the steep zone south of Puerto Barco on the south side of the Catatumbo River, there is evidence of thrust faults dipping toward the east. This latter thrust may be a secondary feature caused by the underthrusting effect of the former one.

Río de Oro anticline.—The Río de Oro anticline is in the easternmost foothills of the Sierra de Perijá in the northern part of the Concession. It trends slightly east of north and extends from the Río Catatumbo to the Río de Oro and some 20 kilometers northward into Venezuela. It is a narrow faulted highly asymmetrical anticline with a nearly vertical east flank and a comparatively gentle west flank. Surface data show two structural highs on the Colombian portion of the anticline, one west of Puerto Barco and the other 4 kilometers south of the Río de Oro. Sandstones of the Barco formation are exposed near the apex of each high.

There are numerous oil and gas seeps along the crest of the anticline. The structural high west of Puerto Barco was tested by two wells which drilled into the upper part of the Uribante formation without encountering production, although there were many oil shows in both Tertiary and Cretaceous. Eleven wells, nine of which were productive, have been drilled on the Colombian portion of the northern high. Production has been obtained from the Catatumbo formation and from the Río de Oro member of the Mito Juan formation. The lower Cretaceous has not been tested on the northern high.

Confluencia dome.—Aerial reconnaissance of the northwesternmost part of the Concession has indicated the probable presence of a low domal uplift south of the con-

fluence of the three principal branches of the Río de Oro, about 15 kilometers northwest of the Río de Oro camp. The Uribante formation is believed to crop out on the Confluencia dome, so it is unlikely that this structural feature is of economic importance.

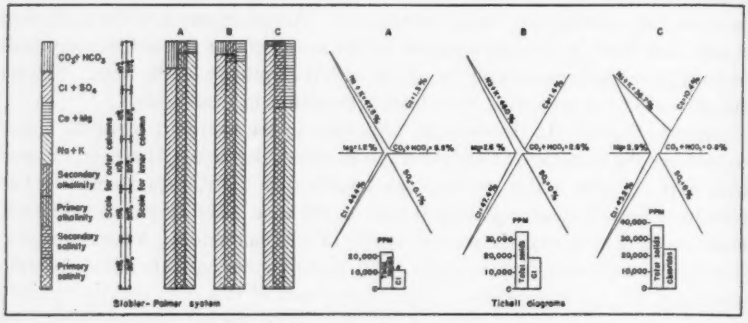


FIGURE 12.—*Water analyses from Petrolea field*
(A) Upper limestones of Guayacán member. (B) Zone 1. (C) Lower Cogollo-Uribante.

FOLDS OF THE SARDINATA DEPRESSION

Location.—The folds of the Sardinata depression are in the central part of the Concession on the west flank of the structural basin between the Petrolea anticlinorium and the foothills uplifts. The line of folding, composed of the Sardinata, Tibú, and Socuavó anticlines, trends slightly west of north and extends at least 60 kilometers.

Sardinata anticline.—The most southerly of the depression folds, the Sardinata anticline, is 9 kilometers west of the Petrolea anticline. It is almost entirely covered by alluvium, and there is surface indication of anticlinal structure only in the southernmost part. Seismic data show a north-south trending slightly asymmetrical anticline with two local highs called Sardinata Sur and Sardinata Norte. The average dip on the flanks is about 10°, and there is no evidence of faulting of major importance. On the La Luna reflecting horizon there is an area of 650 hectares (1600 acres) within a closure of 120 meters on Sardinata Sur and 550 hectares (1350 acres) within a closure of 75 meters on Sardinata Norte. Along the crest of the anticline the León shale underlies the alluvium at an average depth of 15 meters.

No oil or gas seeps have been found on the anticline. The Tertiary and uppermost Cretaceous formations have been tested on both highs without encountering commercial production. Sardinata Sur No. 1 flowed a large volume of dry gas during a drill-stem test of the upper sandstone of the Barco formation, but the other sandstones of the Barco formation are fresh-water bearing although well stained with oil. A sandstone in the Catatumbo made a small pumper, but the well was abandoned as noncommercial at a depth of 1438 meters, in the Mito Juan formation. In Sardinata Norte No. 1 the Barco and Catatumbo sandstones were oil-stained but tight and gave negative drill-stem tests. The well was abandoned as a dry hole at a total depth of 1526 meters, in the Mito Juan formation. The Lower Cretaceous has not been tested on the Sardinata anticline.

Tibú anticline.—The apex of the Tibú anticline, which is really the northern continuation of the Sardinata anticline, is 3 kilometers west of the river port of Tres Bocas. The anticline trends slightly west of north and is slightly asymmetrical with an average surface dip of 15° on the west flank and 6° on the east flank. Seismic data indicate a steeply dipping thrust fault on the west flank, but no faulting was found by surface mapping. There is an area of approximately 6050 hectares (15,000 acres) within a closure of 350 meters on the seismic La Luna horizon.

Three small oil seeps, one with a little gas, occur near the apex of the fold in upper Carbonera sediments. Three wells have been drilled on the anticline, and productive zones have been proved in the Barco and Uribante formations.

Socuavó anticline.—The Socuavó anticline en echelon to the northwest of the Tibú anticline extends from the vicinity of the Tibú camp northward to the Río Socuavó del Norte. North of that stream most of the area is covered by the unconformable Necesidad formation or alluvium, and little is known of the underlying structure. However, seismic lines extending east from Puerto Barco and along the lower Río de Oro show only regional northeasterly dip. Like the Tibú anticline the Socuavó anticline is asymmetrical with a steep, probably faulted west flank and a comparatively gentle east flank. On the seismic La Luna horizon there is an area of approximately 4900 hectares (12,000 acres) within a closure of 250 meters. On the La Luna horizon the Tibú and Socuavó anticlines have a common closing contour. Upper Carbonera sediments are the oldest exposed on the fold.

No oil or gas seeps have been discovered, but several seismic shot holes had oil and gas shows at depths less than 30 meters. Two wells have been drilled on the anticline, and productive zones have been proved in the Barco and Uribante formations.

DEVELOPMENT

RÍO DE ORO FIELD

The first well on the Concession, Oro No. 1, was drilled on the crest of the Río de Oro anticline in 1920 by Doherty interests, offsetting a small producer drilled on the Venezuelan side of the border in 1915 by the Colón Development Company. An oil-bearing sandstone encountered in the Barco formation at 137 meters flowed strongly but soon dropped off to 50 barrels a day and was cased off. The well was abandoned in the Catatumbo formation at a depth of 273 meters. When opened in recent years it flowed fresh water and a very small amount of oil.

Oro No. 2 and Oro No. 3, located on the structural high west of Puerto Barco, were drilled by the Colombian Petroleum Company in the period April 1935 to October 1937. Both penetrated the upper part of the Uribante formation to total depths of 2048 and 1926 meters respectively, without encountering production. Neither well tested the Tibú member. No other wells have been drilled on the southern high of the anticline.

Oro No. 4, located on the crest of the northern high of the anticline 950 meters south of Oro No. 1, was completed in 1937 at a depth of 492 meters, in the top of the Mito Juan formation. It showed a potential of 130 barrels per day on a half-inch choke from a sandstone in the Catatumbo formation.

Since the completion of Oro No. 4 nine wells have been drilled on the northern high, eight of which are productive. The average depth is 430 meters. Two productive

zones in the Catatumbo formation and one in the uppermost Mito Juan formation have been developed. The Lower Cretaceous has not been tested. Production is obtained from fine-grained argillaceous sandstones and siltstones, the intergranular permeability of which is so low that fracturing must be assigned major importance. Effective thickness of sandstones in the productive zones ranges from 3 to 12 meters.

TABLE 1.—*Cumulative production, Barco Concession*

To December 31, 1942, by fields and zones

Field	Zone									Total (Barrels)
	Los Cuervos	Barco	Catatumbo-Río de Oro	La Luna	Cogollo				L. Cogollo Uribante	
					Ostrea	Zone 1	Zone 2	Zone 3		
Carbonera	35,753	46,019								81,772
Petrolea				305,610	479,401	3,849,221	319,707	3,511,831	2,430,847	10,896,617
Río de Oro			64,708							64,708
Tres Bocas		13,093							6,994	20,087
Socuavó		4,627							34,958	39,585
Total	35,753	63,739	64,708	305,610	479,401	3,849,221	319,707	3,511,831	2,472,799	11,102,769

The productive area of the most extensive zone is approximately 170 hectares (420 acres). The average daily potential on a quarter-inch choke is 260 barrels per well with an average gas-oil ratio of 340. The gravity of the oil ranges from 32° to 40° A.P.I. The field has no pipe line connection, so production has been limited to drilling and camp needs. Cumulative production as of December 31, 1942, is given in Table 1.

PETROLEA FIELD

Petrolea No. 1, 200 meters east of the crest of the North Dome, was drilled in 1933. It blew out in Zone 1 of the Cogollo, took fire, and was not brought under control for 47 days. Subsequent to being brought under control the well had to be plugged and abandoned.

Petrolea No. 1-A, 1200 meters southeast of Petrolea No. 1, was drilled in 1933–1934 to a total depth of 917 meters, 17 meters into the basement complex. It was plugged back to 396 meters and completed in Zones 1 and 2, flowing 425 barrels of oil in 12 hours through casing. No conclusive tests of the deeper zones were made.

Between the completion of No. 1-A and the end of 1937, 18 scattered wells were drilled to outline the productive area of the North Dome and to test the South Dome. In 1938 intensive drilling of the North Dome began, and by the end of 1941 130 wells had been drilled, of which 124 were completed as producers, 2 were abandoned because of mechanical difficulties, and 4 were dry holes. Seven wells have been drilled on the South Dome, but only one was productive. It is believed that the present wells will effectively drain the accumulation with the possible exception of Zone 3, which may require a few additional wells. After the intitial exploratory period the wells were drilled on a 400-meter rectangular grid (40 acre spacing) wherever practicable.

Six productive zones have been developed, and these are indicated on the partial log of Petrolea No. 78 which is included in Figure 5; of these, Zone 3 and the Lower

Cogollo-Uribante are the most important. The largest productive area is found in Zone 3, which originally had an area of approximately 1700 hectares (4200 acres). The La Luna formation was productive over only 90 hectares (220 acres). Depth to the productive zones ranges from 20 to 513 meters, the total depth of all wells averaging 317 meters. Of particular interest is Petrolea No. 200, which probably established a record for prolific shallow production. It was located near a large oil and gas seep and was designed to relieve pressure in the shallow La Luna formation. It began drilling the morning of November 14, 1940, and in the afternoon of the same day, while fishing at a depth of 30 meters, the well blew out flowing a solid stream of oil some 2 meters above the $8\frac{5}{8}$-inch conductor pipe. Approximately 5200 barrels of oil was recovered by pumping from a hastily built earthen reservoir during the 10 hours the well flowed before being killed and plugged.

Petrolea crude oil, which is of paraffin base, ranges in gravity from 36.7° to 47.8° A.P.I., the average run from the field being about 46° A.P.I. The gasoline fraction is high, and the lubricating fraction is very low. Cumulative production by zones to December 31, 1942, is shown in Table 1.

Chemical analyses of water samples obtained from various wells show three types of water. Water from the La Luna formation and that from the upper limestones of the Guayacán member of the Cogollo are practically identical. Zone 1 water is very similar but may usually be differentiated by the presence of secondary salinity and the absence of primary alkalinity. No water has been found in Zone 2, and water has been found in Zone 3 in only one well on the Petrolea North Dome. Water from the Lower Cogollo-Uribante is readily distinguishable from that of other zones. Averages of analyses of 20 samples from the upper limestones of the Guayacán member, 4 from Zone 1, and 16 from the Lower Cogollo-Uribante are plotted on Tickell and Stabler-Palmer diagrams in Figure 12.

In the latter part of 1939 a 12-inch pipe line was completed from the Petrolea field to the port of Coveñas on the Gulf of Morosquillo. The line is 421 kilometers long and reaches an elevation of 1611 meters in crossing the Sierra de Perijá.

CARBONERA FIELD

Carbonera No. 1, on Quebrada Carbonera 575 meters east of the surface trace of the Carbonera fault, was completed in May 1938, at a total depth of 830 meters, plugged back to 609 meters. Drilling began near the base of the Mirador formation, and the Mirador was again encountered when the Carbonera fault was cut at a depth of 238 meters. The well was drilled 82 meters into the Catatumbo formation, then plugged back and completed in the Barco formation beneath the fault. On the initial production test the well pumped 46 barrels of 21.5° A.P.I. oil in 24 hours.

Carbonera No. 2, 350 meters east of No. 1, was completed in April 1940, at a total depth of 681 meters, plugged back to 244 meters. Drilling began in the Los Cuervos formation, and the Carbonera fault was cut in the Barco formation at a depth of 379 meters, where the Los Cuervos was again entered. The well was drilled 73 meters into the Barco formation, then plugged back and completed in the Los Cuervos above the fault. On the initial production test the well flowed 82 barrels of 19.6° A.P.I. oil daily through a half-inch choke with pressures of 20 pounds per square inch on the tubing and 180 pounds per square inch on the casing.

Carbonera No. 3, 425 meters northeast of No. 2, was completed in October 1940, at a total depth of 1024 meters, plugged back to 488 meters Drilling commenced near the top of the Mirador formation, and the Carbonera fault was cut in the Barco formation at a depth of 546 meters, where the Los Cuervos was again entered. The well was drilled into the Mito Juan formation, then plugged back and completed in the Barco formation above the fault. On the initial production test the well flowed 65 barrels of 22° A.P.I. oil daily through a quarter-inch choke with pressures of 130 pounds per square inch on the tubing and 200 pounds per square inch on the casing; soon after completion, however, the well began producing a very high percentage of fresh water.

A 3-inch line connects the Carbonera field with the Petrolea gathering system. Cumulative production as of December 31, 1942, is given in Table 1.

TRES BOCAS FIELD

The discovery well of the Tres Bocas field, Tres Bocas No. 1, was designed as a Tertiary test to obtain fuel oil for deeper exploration. It is located near the apex of the Tibú anticline approximately 3 kilometers west of the river port of Tres Bocas. It was drilled in 1939–1940 to a depth of 1646 meters and plugged back to 1207 meters. Drilling began near the top of the Carbonera formation, and the well penetrated 300 meters into the Mito Juan formation. Sandstones in the upper part of the Carbonera formation were stained but produced fresh water. Most of the sandstones below the Mirador formation showed some staining, but on the whole they were poorly developed and unusually tight. The well was completed in the basal sandstone of the Barco formation making 17 barrels daily of 31.2° A.P.I. oil.

Tres Bocas No. 2-A, approximately 800 meters west of No. 1, was designed to test the whole sedimentary section. It was drilled in 1941–1942 to a total depth of 2813 meters, 6 meters into the basement complex. Casing was cemented at 2703 meters, 2 meters below the top of the Tibú member of the Uribante, and the well is producing from the open hole below that point. On the initial production test the well flowed 430 barrels daily of 54.8° A.P.I. oil through a quarter-inch choke with flowing pressures of 2900 pounds per square inch on the tubing and 3140 pounds per square inch on the casing and a gas-oil ratio of 5290. No tests of the Mercedes and Aguardiente members of the Uribante formation were made, but they are believed to be gas or oil bearing.

Tres Bocas No. 3 was drilled in 1942 as an east flank Tertiary test located 2850 meters east of No. 1. It was completed at a depth of 1561 meters, plugged back to 1381 meters. The upper Barco sandstones were found to be fresh water bearing. The well was completed in the lower Barco, pumping 179 barrels of 22.5° A.P.I. oil and 51 barrels of fresh water daily. No other wells have been drilled in the Tres Bocas field.

The wells have been produced only for testing, fuel, and camp use. A 4-inch pipe line has recently been completed from Tres Bocas No. 2-A to the Petrolea gathering system. Cumulative production as of December 31, 1942, is given in Table 1.

SOCUAVÓ FIELD

Socuavó No. 1 (Pl. 2, fig. 2), on the seismic crest of the Socuavó anticline, was completed in March 1942, at a total depth of 3003 meters, plugged back to 2777 meters.

The basement complex was encountered at a depth of 2982 meters. In completing the well, casing stuck and was cemented at 2780 meters. The casing was gun-perforated, and the well was tested at intervals from the top of the plug at 2777 meters to the top of the Uribante at 2543 meters. A small amount of production was obtained from each interval, indicating that the upper half of the Uribante is oil bearing although tight. Acidization increased the production only temporarily. On the initial production test, which included all the perforated intervals, the well produced at a daily rate of 136 barrels of 49.7° A.P.I. oil through a quarter-inch choke with flowing pressures of 1000 pounds on the tubing and 1300 pounds on the casing and a gas-oil ratio of 9547. A year later the plug was drilled out, and an unsuccessful attempt was made to test the Tibú limestones. This well can be classed as a bad completion and an unsatisfactory test.

Socuavó No. 2, a Tertiary test on the west flank of the anticline approximately 6.4 kilometers northwest of Socuavó No. 1, was completed in July 1942, at a depth of 1700 meters, 17 meters below the top of the Mito Juan formation, plugged back to 1512 meters. It was completed by gun-perforating the casing opposite the basal sandstone of the Barco formation. The well produced at a daily rate of 197 barrels of 34.7° A.P.I. oil on a quarter-inch choke with pressures of 250 pounds on the tubing and zero on the casing and a gas-oil ratio of 462. Only drill-stem tests have been made of the upper Barco sandstones; these indicated oil and a little fresh water. A sandstone in the Catatumbo showed brackish water on drill-stem test.

The field has no outlet, and oil has been produced only for testing, fuel, and road oil. Cumulative production as of December 31, 1942, is given in Table 1.

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GRAVITY ANOMALIES DUE TO EXTENSIVE SEDIMENTARY BEDS

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ABSTRACT

Isostatic anomalies result from various two-dimensional structures such as large sedimentary basins and geosynclines. It is shown that a basin should be surrounded by a "halo" of positive anomalies and that the areal extent of the sedimentary layers and the dip of the lower contact are more important than thickness in producing the isostatic anomaly. The computations are applied to a coastal plain in order to interpret Vening Meinesz' findings that on many offshore profiles the anomaly increases algebraically away from the coast. Considerable computations are necessary before one can determine the amount of time lag between the deposition of sediments and the attainment of complete isostatic compensation.

INTRODUCTION

The gravitation field produced by a small geological structure such as a salt dome or an igneous intrusion is relatively easy to visualize and interpret. The nearer one

approaches the anomalous rocks and the larger their volume, the greater is the magnitude of the resulting gravitational force. The force always points toward or away from the anomalous mass and becomes zero only when the distance is very large. Thus it is relatively easy to estimate the size of the structure and the density contrast from the magnitude and shape of the gravity anomalies.

This simple viewpoint is not valid if the geologic structure is so large that it must be assumed to be isostatically compensated. A compensated mass of subnormal density will give negative anomalies for observations immediately above it. As the observation point is moved away, the isostatic anomaly decreases in magnitude to zero. At all more distant points the isostatic anomaly due to the mass deficiency is positive. Because of this reversal of sign with distance it is virtually impossible to make a qualitative correlation between the isostatic anomalies and the known or assumed structural conditions.

In their studies of isostatic anomalies Hayford and Bowie used 2.67 as the density of surface rocks. Bowie (1917, p. 76) has remarked that negative anomalies usually result when the station is situated on Tertiary or Quaternary deposits. Subsequent investigators have made allowance for the deviation of the density of the near-surface rocks from the value of 2.67. Woollard (1938, p. 85) has made a detailed quantitative allowance for this deviation in his studies of the Big Horn region, but many authors such as White (1924, p. 207–208), Swick (1937, p. 333), and Skeels (1940, p. 187) have made only a qualitative correlation between the thickness of the sediments and magnitude of the anomaly.

For extensive deposits of light materials which may be assumed to be isostatically compensated, the thesis is presented that the area and the dip of the contacts are more important than thickness in determining the isostatic anomalies. This contention is demonstrated by curves which show the dependence of the isostatic anomaly on area, thickness, etc., for various geometric configurations which approximate the shapes of sedimentary deposits. In the numerical examples the density of the normal material is assumed to be 2.67 c.g.s., and 2.57 c.g.s. is the density assumed for the sediments. A change to any other density contrast may be obtained by multiplication. Although the computations are based on the method of Hayford and Bowie for a compensation depth of 96 kms., the conclusions reached are valid for the isostatic compensation methods of Vening Meinesz and of Heiskanen.

SIMPLE GEOMETRIC FIGURES

As an example, consider the earth's surface as an infinite plane (Fig. 1 a). A surface layer of light material and of constant thickness that is in isostatic equilibrium will give a zero anomaly. If this infinite layer is reduced to an infinitely long bar 155 miles (250 kms.) wide, then for a depth of compensation of 96 kms. the isostatic anomaly at a surface midpoint, P, is -1.4 milligals for each 5000 feet of thickness and 0.1 c.g.s. density contrast. If this layer is further reduced to a vertical cylinder 155 miles in diameter, the anomaly increases to -2.2 milligals for every 5000 feet in thickness and 0.1 c.g.s. contrast in density.

The isostatic anomaly undergoes a substantial increase in magnitude as the area decreases. This is in striking contrast to the direct effect which for the infinite plane

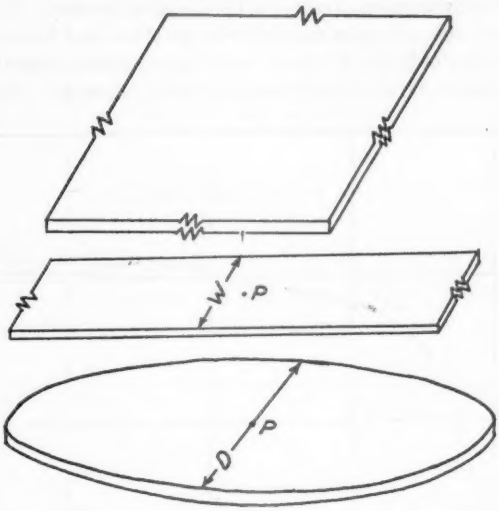

FIGURE 1.—*Various shapes for which a discussion of gravity anomalies is given*

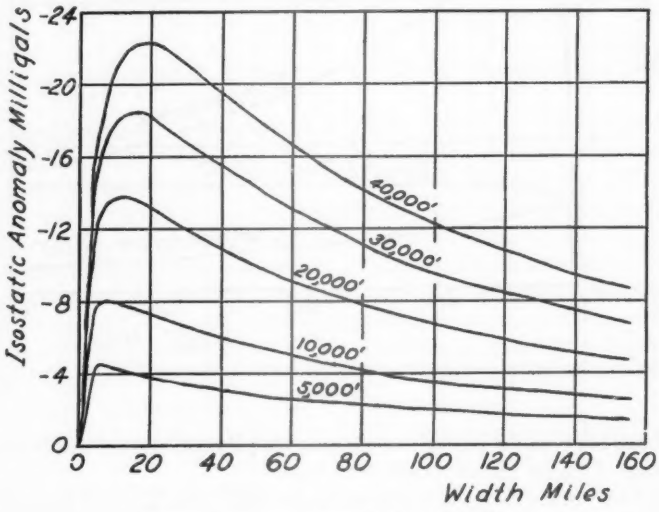

FIGURE 2.—*Isostatic anomaly of an infinite bar*

is −7.0 milligals for each 5000 feet thickness and 0.1 c.g.s. density contrast. The direct effect will decrease very slightly in magnitude in the other cases as the area is decreased.

Bowie (1917, p. 73) has pointed out that the magnitude of the isostatic anomaly is

very dependent on the horizontal extent of the abnormal density. It is repeated here for emphasis and with examples suggestive of synclines and basins. Actually for masses of the shapes of Figure 1 b and c and of any thickness, there is a value of the width, W, or diameter, D, which will give a maximum anomaly. Figure 2 shows the

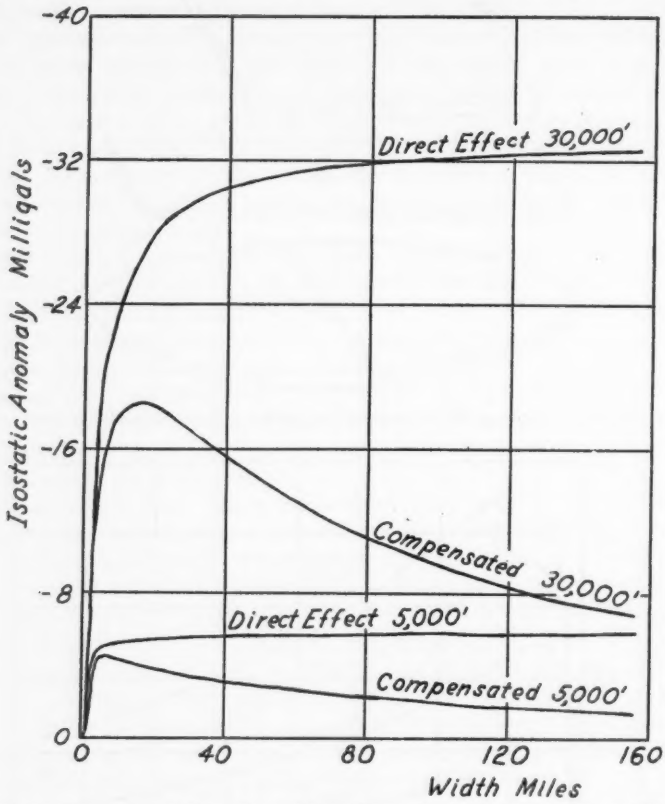

FIGURE 3.—*Comparison of direct effect and isostatic anomaly of an infinite bar for two different thicknesses*

relationship between the isostatic anomaly at the point, P, and the width ,W, of the infinite bar of Figure 1 b for various thicknesses.

When the isostatic anomaly is plotted against the width, W, as in Figure 2, there results a surprisingly sharp maximum. To emphasize the great variance in behavior between the direct effect and the isostatic anomally, comparison curves are plotted in Figure 3 for thicknesses of 5000 and 30,000 feet. These curves show that, in the interpretation of gravity data involving anomalous beds wider than 20 miles, the decision whether or not they are compensated is of critical importance.

Similar curves can be computed for a mass of the shape of Figure 1 c. For thick-

nesses of 5000, 10,000, and 20,000 feet the diameters, D, yielding maximum anomalies are approximately 11.6, 15.4, and 26.4 miles respectively.

These simple considerations show that regions with 10,000 to 30,000 feet of sedimentary material with average density contrast of 0.2 to 0.3 c.g.s. as in the East Texas Embayment and the Gulf Coast may produce anomalies of from −6 to −40 milligals.

EFFECT OF RATE OF DIP

Computations for two-dimensional structures are presented to substantiate the thesis that the rate of dip is more significant than the thickness of the sedimentary layers. All computations are made graphically for a Hayford-Bowie type of compensation of depth 96 kms.

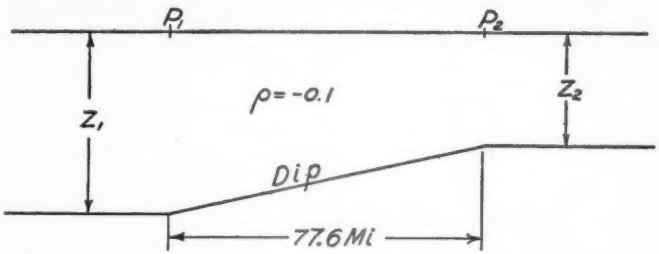

FIGURE 4.—*Two-dimensional structure for which isostatic anomalies (at points P_1 and P_2) are computed*

Consider the simple two-dimensional structure of Figure 4. Figures 5 and 6 show isostatic anomalies for the points P_1 and P_2 respectively computed as functions of the depth Z and of the rate of dip. The curves of Figures 5 and 6 show that if a change of the dip of an interface is convex to the surface a positive anomaly results, whereas if the change in dip is concave to the surface the anomaly is negative.

From these considerations one expects a rim of maximum anomalies around the edge of a basin whose position coincides with the edge or sudden thickening of the light basin material and whose magnitude is almost directly proportional to the dip of the contact. This is in contrast to the conclusions reached from the assumption that the basin is uncompensated. If the basin is uncompensated, there is only the direct effect of a mass deficiency which will be negative everywhere.

In a paper on basin structures Skeels (1940) presents some gravity profiles and geologic profiles. Figures 3 and 4 of his paper show this "halo" pattern nicely.

Consider the extensive monocline of Figure 7. For values of Z from 5000 to over 25,000 feet the isostatic anomaly at P is independent (within 0.1 milligal) of the value of Z and depends only on the rate of dip. Two aspects of this relationship (Fig. 8) deserve emphasis: (1) the anomaly is independent of the thickness, and so any correlation between the anomaly and the thickness of the formation is unwarranted; and (2) the anomaly due to an extensive monocline is less than one milligal for thicknesses as large as 25,000 feet and dips as large as 250 feet per mile.

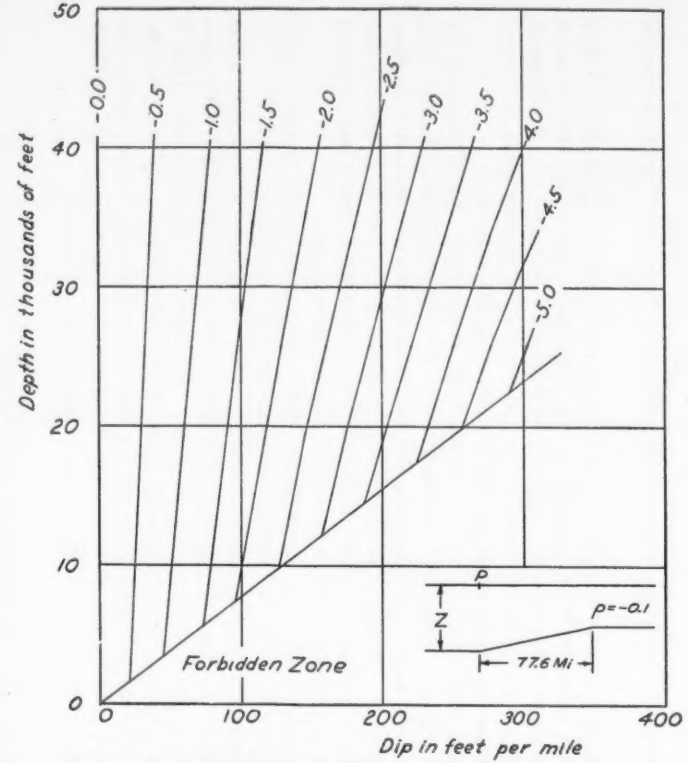

FIGURE 5.—*Curves showing isostatic anomaly (at point P) as a function of depth (Z) and dip*

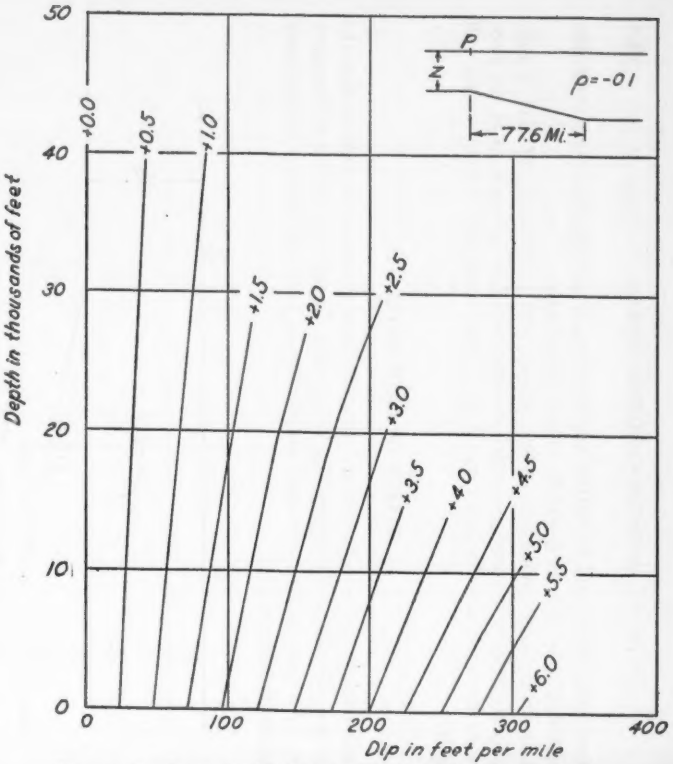

FIGURE 6.—*Curves showing isostatic anomaly (at point P) as a function of depth (Z) and dip*

Exact detailed conclusions cannot be made from these illustrations because of the assumption that the sedimentary layers are infinite in extent. Three general conclusions, however, can be reached:

(1) If the dip changes so that the contact is concave to the surface a negative

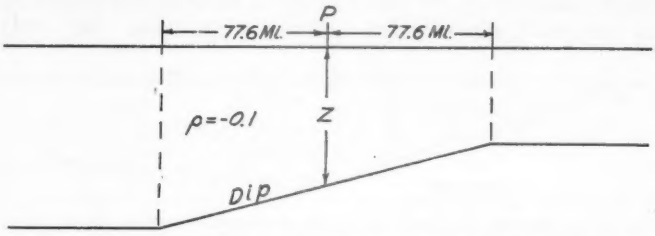

FIGURE 7.—*Two-dimensional structure for which isostatic anomaly (at point P) is computed as a function of depth (Z) and dip*

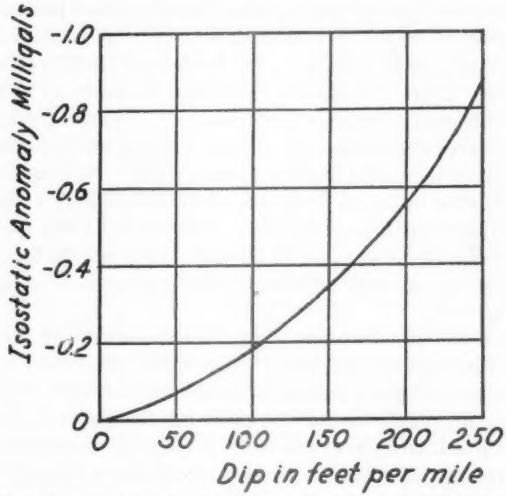

FIGURE 8.—*Isostatic anomaly as a function of dip for the two-dimensional structure of Figure 7*

anomaly results. This is true even if, as at P_2 in Figure 4, the top of the basement does not have a structural low.

(2) If the dip changes so that the contact is convex to the surface a positive anomaly results. This is true even if, as at P_1 in Figure 4, the top of the basement does not have a structural high.

(3) If the contact between the sedimentary veneer and the underlying basement is an extensive monocline, the gravity anomalies are negative, depend almost entirely on the rate of dip, and are very small even for substantial thicknesses and rates of dip. It will be noted that these statements refer to the structure of the base of the light

material. If this light material is submerged, the effects of the upper contact will be opposite sign to the rules stated.

APPLICATION TO GRAVITY ANOMALIES OF COASTAL PLAINS

Vening Meinesz (1934, p. 99) remarked that on many offshore profiles the gravity anomaly increased algebraically with the distance from shore. Daly (1940, p. 296-

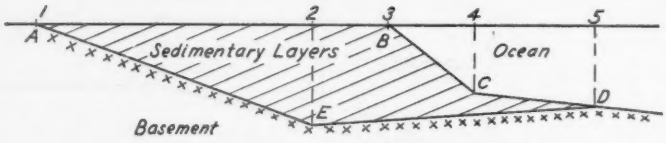

FIGURE 9.—*Generalized picture of structure of a coastal plain*

297) quotes a statement made by Vening Meinesz in 1939 that the refraction profiles measured by Ewing and his associates give a satisfactory explanation of this occurence. Let us consider a gravity profile across a typical coastal plain and examine the relationship between the dip of the contacts and the gravity anomalies.

In view of the studies of Ewing, Crary, and Rutherford (1937) a generalized picture of the sedimentary layers of a coastal plane may be drawn as in Figure 9. The shaded region represents a wedge of light material. When a gravity profile across this region is measured and the isostatic anomally is computed, allowance is made for the water and its corresponding isostatic compensation. No correction, however, is made for the deviation in density from 2.67 of the sedimentary wedge or of the isostatic compensation of this mass deficiency. Therefore, to a first approximation, the computed anomalies resulting from the observed data should be the same as the isostatic anomalies due to a negative mass of suitable density and of the same shape as the wedge of Figure 9.

The behavior of the isostatic anomaly can be determined with the aid of the rules stated above. First consider the lower contact AED. At A there is a change of dip convex to the surface, and so a positive anomaly will be found. On the long monocline AE the anomaly rapidly becomes zero and then changes to small negative values. The change in dip at E is concave to the surface and so gives a negative anomaly. If the dip AE is large, the negative anomaly due to the change in dip at E will be large even if the dip ED is so small that the minimum at E is not a pronounced syncline. This shows one danger of predicating the existence of a geosyncline solely on the basis of a pronounced gravity minimal axis. At D the anomaly will be positive or negative according as the dip CD is smaller or larger than the dip ED.

Along the top of the wedge ABCD the dip AB is zero and so contributes nothing. At B the change in dip is convex to the surface but since this is the upper contact a negative anomaly results. The dip from B to C will give positive anomalies, and at C the pronounced change in dip will give a large positive value.

The changes of dip at both E and B yield negative anomalies and so if they differ in location a zone of minimum anomalies between 2 and 3 will result.

A gravity profile normal to the coast line should give gravity anomalies that are positive at the edge of the outcrop, negative along most of the near-shore region with minimum values between the line of maximum thickness of sediments and the edge of the continental shelf, and positive near the edge of the ocean basin. At point 4 of Figure 9 the negative effects of E and B may be large enough to mask the positive effects of C. This will result in a pushing of the region of positive values toward the ocean. The curves of Figures 5 and 6 predict the observed fact that on going from the coast to the ocean the isostatic anomalies increase algebraically.

OBSERVED GRAVITY ANOMALIES OF THE GULF AND ATLANTIC COASTAL PLAINS

When the isostatic anomalies of the U. S. Coast and Geodetic Survey gravity stations are contoured, it is found that a minimal axis extends from the Mexican border west of Brownsville (Sta. 724) along the Gulf Coast to Florida (Sta. 869). Although the contours are somewhat disturbed in the northern part of Florida, the minimal axis may be traced from Florida to New York. Along this latter trend the minimum values seem to occur between the shore line and the edge of the continental shelf, but in most places stations are located only on the western flank. Along the Gulf Coast the minimal axis is believed to coincide with point 2 of Figure 9, whereas along the Atlantic Coast it is believed to occur somewhere between points 2 and 3.

Inland from this minimal axis there is in most places a maximal axis believed to coincide with the zone of sudden thickening of the sedimentary layers. Along the Gulf Coast this axis is greatly distorted by the East Texas Embayment, the Mississippi Embayment, and the projection of the Appalachians into Alabama. Along the Atlantic Coast the maximal axis can be traced north from Station 162.

In his study of a gravity profile across Virginia, Woollard (1939, p. 317) has shown shown that at least part of the gravity maximum near the Fall Line on this particular profile is due to an intrusive mass of heavy density and large seismic velocity. This does not invalidate the general principle that the coastwise maximal axis coincides with the zone of sudden thickening of the sedimentary layers.

USE OF GRAPHS TO ESTIMATE ANOMALIES

The curves of Figures 4 and 5 are useful in the quick estimation of the isostatic anomaly produced by a two-dimensional body. Their usefulness depends on the fact that the isostatic anomaly at the edge of a semi-infinite sheet is zero. For example in Figure 10 the anomaly at B due to the structure NOPQR can be computed as follows: From Figure 6 the effect of the boundary NOPS can be determined. Of this material the contribution of the mass CBPS is zero. Likewise the anomaly due to the boundary MPQR can be determined from Figure 6. The contribution of the mass ABPM is zero. Therefore the anomaly due to the surface NOPQR can be obtained as the sum of two readings from Figure 6. If the points O and Q are more than 77.6 miles from P, very little error will be introduced.

REGIONS OF ACTIVE DEPOSITION

From a detailed knowledge of the isostatic anomaly in regions of active deposition such as the deltas of the Nile and Mississippi rivers one should be able to solve many of the problems of isostasy. For example it could be determined to what extent the sediments are compensated, and conclusions could be reached regarding the strength

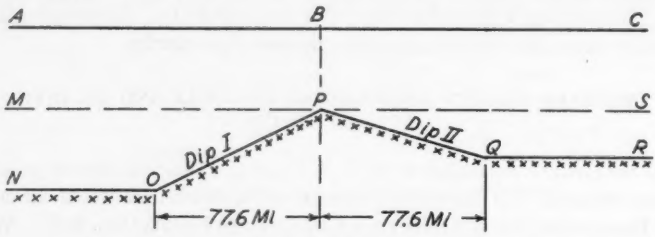

FIGURE 10.—*Two-dimensional structure*

of the earth's crust. It would also be possible to determine how much time lag exists between the deposition of a load and the completion of isostatic compensation. Bowie (1924) and Vening Meinesz (1930; 1934) have made some measurements on the deltas of the Mississippi and the Nile rivers. In each case the tentative conclusion has been reached that there is no lag in the attainment of isostatic compensation. These conclusions (Bowie, 1924, p. 50; Vening Meinesz, 1930, p. 77; 1934, p. 109) are based on the fact that the isostatic anomalies are negative in sign.

The computations presented in this paper are based on the assumption of complete isostatic equilibrium and consequently cannot be applied directly to sediments which may be only partially compensated. In view of the wide range of positive and negative anomalies that may result depending on the shape of the bottom of the sedimentary layers it is impossible to base any conclusions on a simple inspection of the gravity data. It will be possible to interpret the gravity anomalies correctly only when the areal extent and thickness of the sediments are known. Then the resulting anomaly can be computed with the assumption of various degrees of compensation until agreement with the observed value is obtained.

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DISTRIBUTION OF RADIOACTIVITY IN ANCIENT SEDIMENTS

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ABSTRACT

By the use of beta-ray counters a method has been developed for the determination of the three radioactive constituents in ancient sediments—potassium, thorium, and uranium. Owing to the high efficiency of the counters to beta radiation only 3 grams of sample are required. The apparatus is calibrated with radioactive standards. Over 300 samples representing several distinct types of sedimentary rocks have been measured. The highest concentration of all three radioactive constituents was found in the Antrim formation, an organic black shale of Mississippian-Devonian age in Michigan. Similar characteristics were observed in the Chattanooga formation from wells in

Oklahoma. These black shales show maxima of organic matter, uranium, thorium, potassium, colloidal size grades, and thorium/uranium ratio. The radioactivity measurements are complicated by the high emanating power of these shales. Logs of beta-ray activity, alpha-ray activity, and estimated per cent black shale have been made on cuttings from Pure No. 3 Gingrich, Osceola County, Michigan, between depths of 1600 and 3200 feet. These logs include the Marshall and Ellsworth formations, the Antrim shale, and the Traverse limestone. The results indicate significant variations in the distribution of radioactive elements and organic materials in these sedimentary rocks. It is concluded that the principal loci of radioactivity are (1) in heavy minerals in sands and sandstones, (2) in potassium-bearing sediments, and (3) in sediments of colloidal deposition. These relationships are of possible importance in defining the source beds of petroleum.

INTRODUCTION

The radioactivity of sediments and sedimentary rocks is of increasing importance to geologists. It is now well established that essentially all terrestrial materials contain significant quantities of radioactive elements. The radiations from these elements are the chief source of geothermal energy and produce chemical changes in underground fluids. The use of radioactive elements as tracers in the study of sedimentation may aid in defining the source beds of oil. The chemical changes caused by radioactivity may be of importance in the conversion of organic substances. These facts make it necessary to include a consideration of radioactivity in a comprehensive investigation of the origin of petroleum.

Numerous quantitative determinations of the radioactivity of igneous rocks have been made. Relatively few sediments or sedimentary rocks have been measured (Bell, Goodman, and Whitehead, 1940). Therefore, the present research was undertaken to provide not only further precise measurements on sediments but to afford data on which to evaluate the role of radioactivity in the genesis of petroleum.

Three types of radiation are emitted by radioactive elements—namely, alpha, beta, and gamma rays (Figs. 1–3). While any one of these radiations may be used for measurement, each has its particular range of applicability. Alpha-ray ionization allows an unambiguous determination of radium on small quantities of sample but requires that the radon in equilibrium with the radium be released and held under observation for several hours. Similar techniques are available for the determination of thorium using flow measurements of the gaseous thoron. Direct alpha counting gives the sum of uranium plus thorium but also requires extended observations and detailed treatment of sample. Gamma-ray measurements while more rapid are considerably less sensitive and generally require several kilograms of sample. The present technique is somewhat less sensitive than the alpha-counting method but has the following distinct advantages: (1) only simple treatment of the sample is required, (2) a few minutes instead of several hours suffice for a measurement, and (3) only a few grams of sample are needed. The third advantage is particularly important in the study of oil-well cuttings since the quantity of sample available is frequently limited to only a few grams. A fourth consideration that is partly advantageous and partly objectionable is that potassium also contributes to the total beta activity.

Foremost among the requirements of this research was the need for standardization and calibration of instruments and methods. Much of the earlier work in this field has been qualitative, including the logging of wells by gamma radiation. The present work was begun with the principal objective that all measurements be made on a quantitative basis.

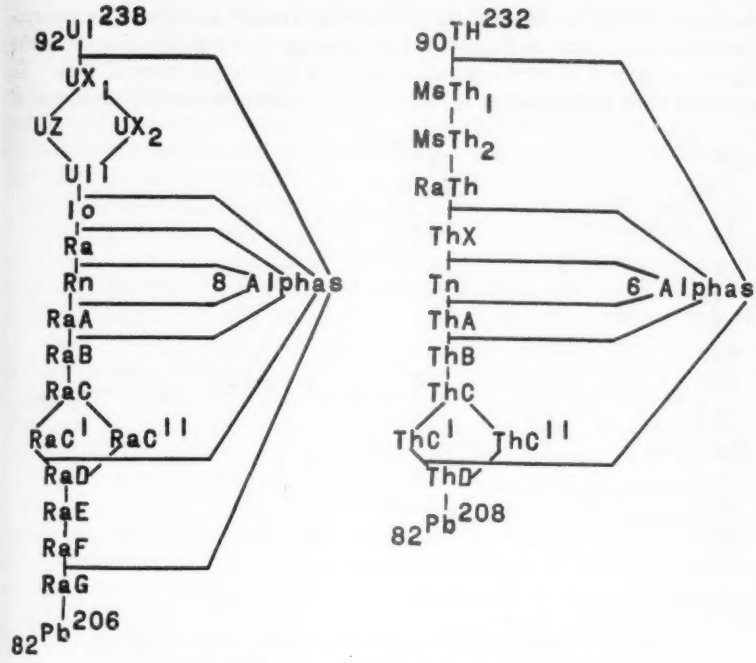

FIGURE 1.—*Alpha-ray emitters of important terrestrial radioactive elements*

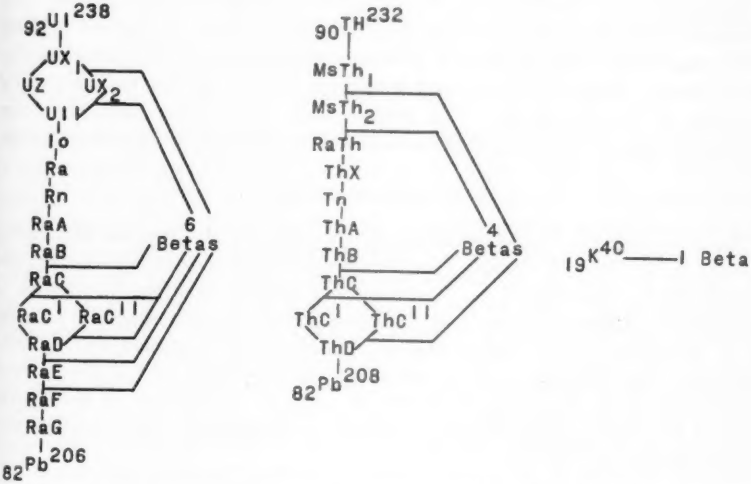

FIGURE 2.—*Beta-ray emitters of important terrestrial radioactive elements*

Pontecorvo (1942) has reported the results of an attempt to standardize gamma-ray measurements. The sensitivity of his apparatus limits observations to rocks containing at least 5×10^{-12} equivalent grams of radium per gram of rock. To obtain significant measurements on all types of sedimentary rocks, the range of

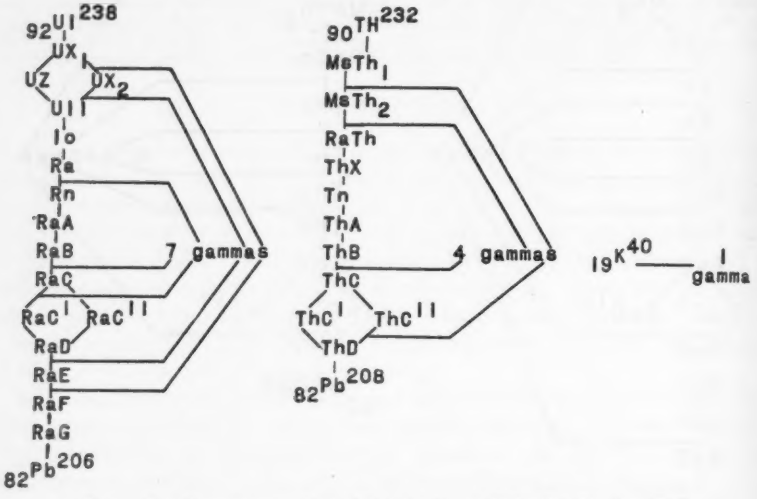

FIGURE 3.—*Gamma-ray emitters of important terrestrial radioactive elements*

observation must include pure quartz sands, limestones, and other less active rocks which often contain less than 0.1×10^{-12} grams of radium per gram.

Among the more recent studies, Piggot (1938) suggested that radioactivity may be related to the heavy-mineral composition of igneous rocks. Evans and Williams (1938) observed a rough relationship between radioactivity and the potassium content of lavas. Barth (1938) proposed certain correlations between radium and the petrology of Finnish granites. The present work has revealed additional correlations that may be significant in the genesis and identification of sedimentary rocks.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to Mr. Ira H. Cram and Mr. Theron Wasson of The Pure Oil Company for their generous provision of well cuttings and geologic data. Professor W. L. Whitehead has aided in relating the research to the field of petroleum geology and in preparation of the manuscript. Professors W. J. Mead and R. R. Shrock provided generous encouragement and valuable criticism. The determinations of potassium and of carbon and hydrogen were made by Mr. S. Y. Tyree and Mr. Robert B. Giles, Jr., respectively, of the Department of Chemistry, Massachusetts Institute of Technology. The counters were constructed by Mr. Ed Barr.

APPARATUS AND METHODS OF MEASUREMENT

GENERAL CONSIDERATIONS

For rocks more than a million years old, it can generally be assumed that the three radioactive series are in equilibrium. Under these conditions the total number of beta or alpha particles emitted per unit time by a particular series is directly proportional to the concentration of any individual member of the series.

Measurements of potassium acivity are expressed in terms of the concentration of potassium alone since there is only one radioactive isotope, K^{40}. The determination of potassium is made possible by its beta emission and the assumption that the abundance ratio of K^{40}/K^{39} is constant (1:8500, Nier, 1936), regardless of the geologic age of the potassium-bearing rock (Smythe, 1939; Cook, 1943). While potassium also emits 2 Mev gamma rays, the ratio of the number of quanta to the number of beta rays emitted is only about 3:100. For this reason the importance of potassium in gamma-ray logging is less than has generally been supposed.

Uranium and thorium may be determined by measurement of alpha, beta, or gamma rays. The direct fusion method (Evans and Goodman, 1941) affords an unambiguous method of determining the radium content of terrestrial materials from the ionization produced by the alpha rays from radon. Under equilibrium conditions uranium may be computed from these measurements. Thorium may be determined either by the flow method (Goodman and Evans, 1941) or by measurement of the total alpha activity of rocks together with a separate radium determination (Evans and Goodman, 1944). These methods involve measurement of alpha particles over a period of several hours.

Members of the uranium and of the thorium series emit gamma radiation in measurable quantities. Evans and Mugele (1936), Pontecorvo (1942), and Russell (1944) have reported the results of gamma-ray measurements on rocks using Geiger counters. Except for rocks of unusually high radioactive contents, large quantities of sample, up to several kilograms, are required for such measurements.

BETA COUNTER

Gingrich, Evans, and Edgerton (1936) and Evans and Alder (1939) have described the counting-rate meter employed in this work. This apparatus has been used extensively for a number of different gamma-ray measurements. When the present research was initiated, this instrument had also been used for a limited number of beta-ray measurements of biological materials. Because the samples to be studied were largely well cuttings, which seldom have a mass of more than 50 grams, the conventional gamma-ray method was obviously not suitable. Brown and Evans (1938) had suggested increasing the efficiency of gamma-ray counters by placing the sample inside a hollow coaxial anode. Several experimental models of this type were constructed and found to be unsatisfactory because of the presence of frequent, unexplained spurious counts. Accordingly, a thin-walled Geiger-Muller type, beta-ray counter (Fig. 4) was constructed and found quite satisfactory. The cathode of this counter consists of an aluminum tube 7 inches long, $1\frac{5}{8}$ inches in diameter,

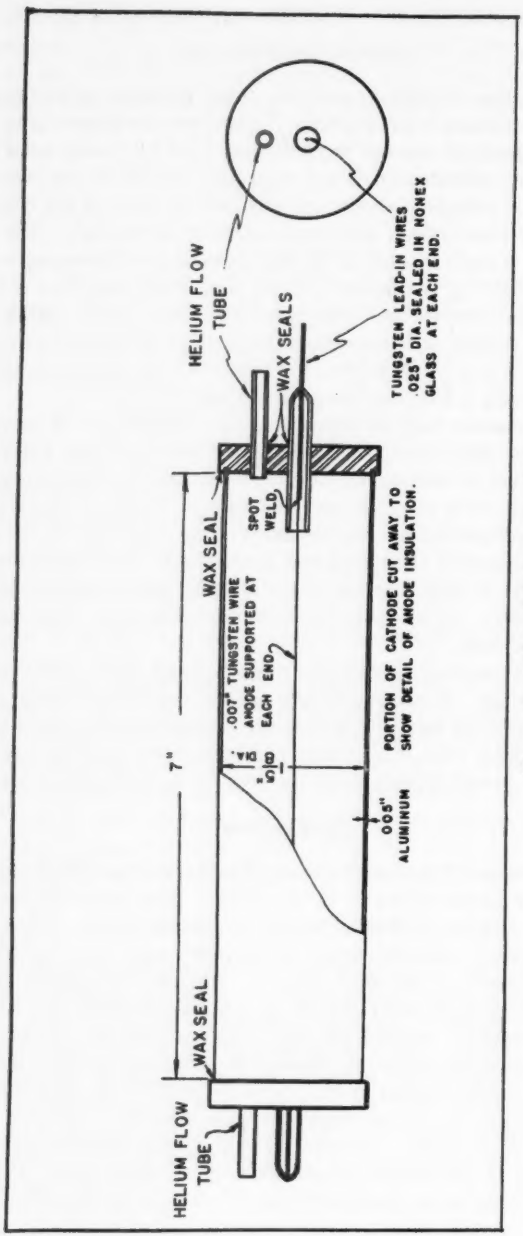
HELIUM FLOW TUBE
WAX SEALS
TUNGSTEN LEAD-IN WIRES .025" DIA. SEALED IN NONEX GLASS AT EACH END.
WAX SEAL
SPOT WELD
.007" TUNGSTEN WIRE ANODE SUPPORTED AT EACH END
PORTION OF CATHODE CUT AWAY TO SHOW DETAIL OF ANODE INSULATION.
7"
.005" ALUMINUM
WAX SEAL
HELIUM FLOW TUBE

FIGURE 4.—*Thin-wall beta-ray counter*

having a wall thickness of .005 inch. The cathode is cemented into brass end pieces with sealing wax. The anode is a tungsten wire .007 inch in diameter, having an effective length of 5½ inches. The ends of the wire pass through glass insulating tubes which are waxed inside the brass end pieces. Small lengths of glass tubing are also arranged to permit the flow of helium through the counter. Coaxial with the cathode on the exterior is a flexible celluloid jacket supported on lead bands at the ends of the counter and held in place approximately 2 mm. from the outside of the aluminum wall. This celluloid envelope has an opening 7 inches long and ¾ inch wide at the top.

OPERATION OF BETA COUNTER

The sample is poured through the slot in the celluloid envelope and fills the annular space surrounding the counter. Using a rock sample ground to pass 20 mesh and be retained on 100 mesh, the counter envelope can usually be filled or emptied in a few seconds.

Throughout the period when the counter is in operation and for several hours prior to the actual measurements, helium flows slowly through the interior of the counter. The outlet tube of the counter is connected to a small trap containing vacuum-pump oil so that the rate of flow of helium may readily be observed. If air is permitted to contaminate the interior of the counter, its operation will not be satisfactory until the foreign gases have been thoroughly flushed out. The anode wire must be centered carefully and kept in sufficient tension to maintain its position.

Each individual counter has its optimum operating voltage range, determined by observing the counting rate for a fixed, active source over a wide range of applied voltages. Counting begins at a certain threshold potential (*ca.* 1600 volts). At about 2000 volts the number of counts per minute remains relatively constant over a range of approximately 100 volts, called the "plateau." Above the plateau the number of counts again increases rapidly, and at a maximum value of about 2400 volts a continuous discharge takes place. Ordinarily the plateau is sufficiently wide that, when the applied potential is in the middle of the range, fluctuations in the line voltage do not affect the rate of counting. Changes in barometric pressure and humidity necessitate occasional redetermination of the plateau.

The counter is surrounded by inactive lead 2 inches thick to reduce the natural background counting rate resulting from cosmic radiation and stray beta and gamma rays. The effective background depends to some extent upon the absorption of these radiations by the rock sample surrounding the counter. With no sample in the celluloid envelope one shielded counter had a background of approximately 100 counts per minute. The absorption of the stray radiation by a rock sample surrounding the counter reduced this background to 78 counts per minute. Measurements of the absorption by rocks of different densities were made. The absorption was observed to be an exponential function of the effective density of the rock sample surrounding the counter. This density involves not only the intrinsic density of the rock itself but the size distribution of the ground sample and the degree of packing among the constituent particles. To render all the observations as nearly uniform as possible with regard to packing, the volume of the counter envelope was

determined with normal packing of the sample. For No. 101 counter, which was used in the calibrations, a volume of 40.5 cc. normally surrounds the counter wall with a sample uniformly 2 mm. in thickness. The mass of this volume of sample varies from 25 to 65 grams depending upon the intrinsic density of the rock.

STATISTICS

There is of course a statistical distribution in the number of beta particles registered by the counter per minute. Observations must be taken over a period of time sufficient to reduce the experimental uncertainty to the desired value. For most samples an uncertainty of less than 10 per cent was obtained in 15 to 30 minutes. The fluctuations during these periods were recorded by a graphic milliammeter connected to the output of the counting-rate meter. Typical records are shown in Figure 5. The time constant of the counting-rate meter and the associated graphic milliammeter is such that considerable averaging is achieved. At any instant the recorded number of counts per minute is the average of the immediately preceding 60 seconds.

CALIBRATION

An attempt was made to predict theoretically how many counts would be expected from a sample of known radioactive content. Because of the uncertainties in absorption coefficients, in the number and energies of the beta and gamma rays from the various series of elements, and in the efficiency of the counter for these radiations, only a rough estimate could be obtained. Hence an empirical calibration was necessary. Standard rock samples were prepared with the densities and activities expected in well cuttings. Three different materials—namely, plaster of paris, granulated alumina, and pure olivine—were chosen for this purpose. These materials were selected because of their range in densities and because of their almost complete lack of intrinsic radioactivity. The standards ranged in activity from the lowest to values well above the maximum expected in sedimentary rocks. As a source of potassium, chemically pure crystalline KCl was employed. As a source of thorium, Brazilian monazite sand containing 5.29 per cent of thorium was used. Carnotite ore containing 1.58 per cent of uranium as certified by Ledoux & Company of New York was used in the uranium standards. The thorium and uranium minerals were contributed by Professor Robley D. Evans and are portions of the same standards used in his gamma-ray studies of terrestrial materials (Evans and Mugele, 1939). Owing to the high emanating power of the carnotite, the powdered samples prepared therefrom gave nonreproducible results. Evidently during the grinding of the carnotite into the fine powder to be mixed with the matrix, sufficient radon escaped to destroy the radioactive equilibrium. To establish calibration curves for the uranium series another type of standard had to be prepared.

The procedure used in calibrating the counter for the potassium and thorium series was as follows. A volume of 40.5 cc. (mass 36 grams) of standard was placed in the counter envelope and its activity measured for approximately 30 minutes. Prior to each run of a standard sample, a similar matrix containing no added radioactive material was placed in the counter to determine the background. Subse-

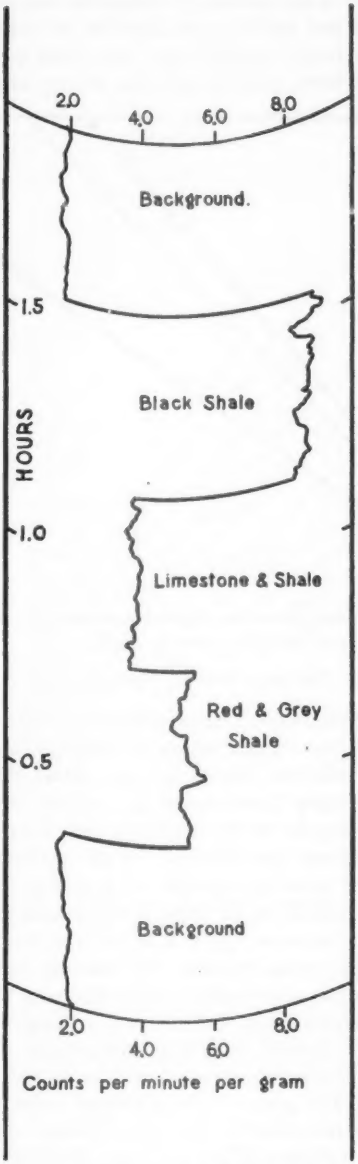

FIGURE 5.—*Typical record of beta-ray counts*

quent to each run another background determination was made, and the average of the two backgrounds was used in computing the net counts from the standard. For standards of low activity, repeated runs were made to insure reproducibility. As expected, plaster of paris, with an effective density of 0.58, gave the largest

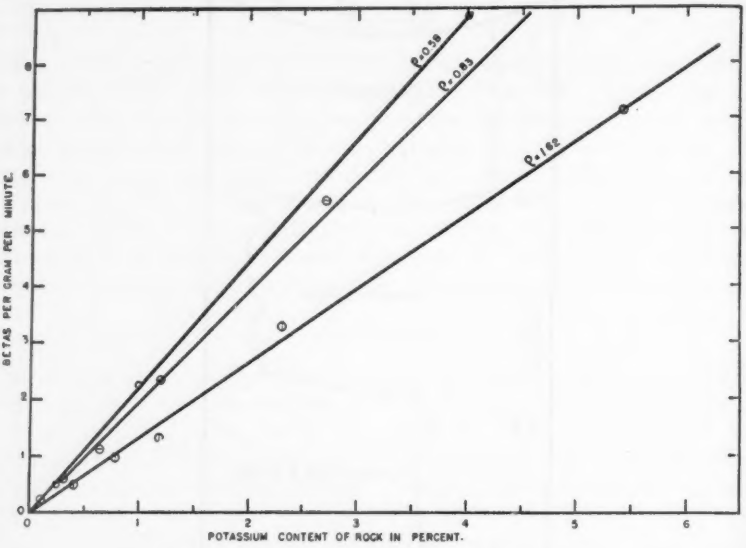

FIGURE 6.—*Beta-ray absorption curve*

number of counts per minute for a given radioactive content. Alumina, with an effective density of 0.83, has a higher degree of absorption and gives a lower count, while olivine, with an effective density of 1.62, shows the greatest absorption. (*See* Figure 6.) From these three curves, an activity-density curve, shown in Figure 7, has been prepared for use in connection with sedimentary rock samples.

Similar calibration curves were obtained for the uranium and thorium series. From these three sets of curves it is possible to determine the equivalent uranium, thorium, or potassium activity of an unknown rock sample but not the separate concentrations of these elements. In a study of the distribution of radioactive substances in sedimentary rocks, however, it is desirable to know these concentrations. A chemical analysis of potassium would eliminate the necessity of such a determination by radioactive means, but this was not possible for the large number of samples investigated. Instead, a fairly reliable estimate of the potassium can be made, based on the following reasoning: Members of the uranium and thorium series emit alpha, beta, and gamma rays; potassium emits mainly beta rays with few gamma rays. Determination of the alpha activity alone, therefore, gives a measure of the sum of uranium and thorium, but not of these two separately. Because of fortuitous compensating effects in the two series, the beta activity equivalent to a given measured alpha activity is practically independent of whether the radioactivity is from the uranium or the thorium series. (*See* Figure 8.) Hence the

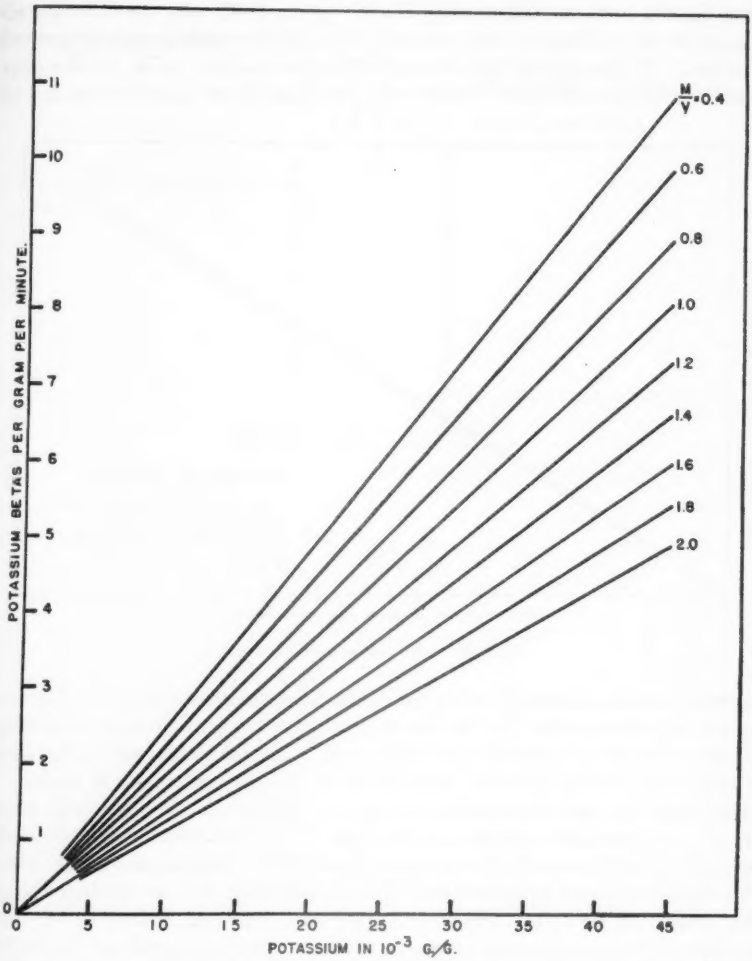

FIGURE 7.—*Activity-density curve*

potassium beta activity represents the difference between the observed total beta activity and the equivalent beta activity estimated from the measured alpha activity. The accuracy of the estimate increases with the potassium content of the sample.

Several attempts were made to prepare calibration curves of the counter for the uranium series. The use of carnotite ore containing a known amount of uranium soon revealed that the measurements were not reproducible because of the excessive emanating power. The use of this material was temporarily discontinued while further search was made for suitable calibration standards.

The series of rock standards established by the National Research Council Com-

mittee on Standards of Radioactivity (Curtiss *et al.*, 1940) offer the following advantages for intercalibration and standardization: (1) The radium contents are well established, (2) the samples have favorable thorium/uranium ratios, (3) the range of radium contents coincides favorably with the values found in sediments, and (4)

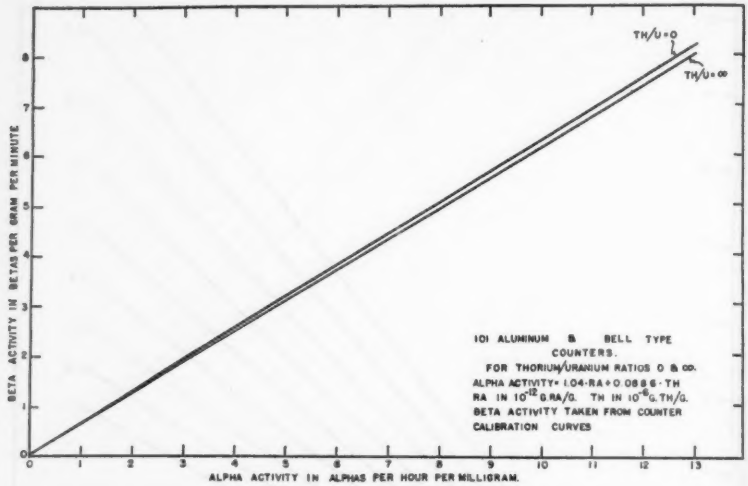
TH/U=0
TH/U=∞
101 ALUMINUM 8 BELL TYPE COUNTERS.
FOR THORIUM/URANIUM RATIOS 0 & ∞.
ALPHA ACTIVITY= 1.04·RA+0.088·TH
RA IN 10^{-12} G RA/G. TH IN 10^{-6} G. TH/G.
BETA ACTIVITY TAKEN FROM COUNTER CALIBRATION CURVES
BETA ACTIVITY IN BETAS PER GRAM PER MINUTE
ALPHA ACTIVITY IN ALPHAS PER HOUR PER MILLIGRAM.
0 1 2 3 4 5 6 7 8 9 10 11 12 13

FIGURE 8.—*Beta-alpha-activity curve*

accurate chemical analyses including the potassium content are available. The only major disadvantage is that the thorium contents have not been measured accurately. As part of the present research total alpha-activity measurements were made of this series of rocks, thereby allowing estimates of the thorium contents to be made.

Consistent beta and alpha measurements were obtained on the basic rocks whose uranium and potassium contents are relatively low. The acidic rocks, particularly the granites which possess high uranium and potassium contents, gave widely different results in repeated measurements. This inconsistency is to be attributed to the high emanating power of these rocks. They are, therefore, unsuitable for beta- and alpha-calibration purposes unless the radon and thoron are confined. A further search for suitable calibration standards was made with the highly active organic black shales. Separate measurements of potassium, radium, and total alpha activity revealed that these rocks also possess high emanating power and are unsuited for calibration purposes without adequate precautions.

Finally cylindrical samples of plaster of paris were cast containing carnotite ore in concentrations of 5.0, 10.0, and 25.0 $\times$ 10^{-6} g. U/g. The total beta activity of these samples was determined by the use of a bell-type counter (Fig. 9) having a mica window 25 micra thick, of the same diameter as the sample. After initial measurement each sample was coated on the exposed surface with a thin layer of cellulose acetate (about 0.2 mg. per sq. cm.). Measurements confirmed that a

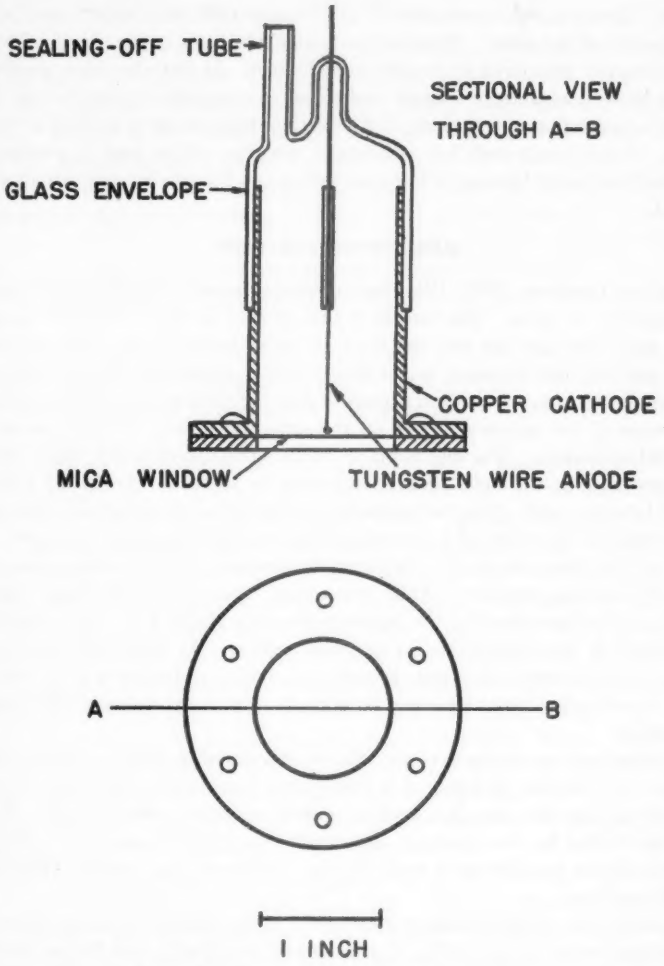

FIGURE 9.—*Schematic drawing of bell-type counter*

negligible amount of beta radiation was absorbed by the acetate film. The samples were then stored for 30 days, and the total beta radiation was again measured after equilibrium had been restored in the uranium series. These measurements gave the true beta radiation from the known concentration of uranium.[1] By the addition of finely ground olivine the density of the mix, when dried, was increased to 1.62. From these two series of standards final calibration curves were prepared.

By coincidence the bell counter and the cylindrical counter had identical cali-

[1] It is well established that the thorium content of Colorado carnotite is negligible.

brations. Hence samples measured in one counter yield data which may be used for calibration of the other. This was particularly valuable in the use of calibration rocks when the quantities of sample were limited. It has also been possible to measure small quantities of organic shales and to interpret the significance of the findings in connection with the bulk of observations made in the cylindrical aluminum counter. In all future work bell counters of this type will be used in preference to the cylindrical model because of the convenience and the smaller quantity of sample required.

ALPHA COUNTING METHODS

Evans and Goodman (1941; 1944) have developed a method to determine the total alpha activity of rocks. The sample is first ground in ethyl alcohol in an agate mortar until the particles are less than 10 micra in thickness. The mixture of alcohol and fine rock is poured over a thin copper or aluminum disc and evaporated at room temperature. A uniform deposit of finely divided rock particles is obtained.

The mass of the sample mounted on the supporting metal disc may range from 50 to 100 milligrams. The disc is placed in an ionization chamber where the ionization produced by the alpha rays emitted from the source is collected by a suitably arranged electric field. This ionization is amplified either by a vacuum-tube electrometer circuit or by means of a four-stage linear amplifier recently developed. The output of the linear amplifier is delivered to a power amplifier which operates an automatic printing register. When the voltage pulse from the linear amplifier exceeds a value determined by the bias voltage on the grid of a thyratron, an impulse is delivered to the counter on the printing register. At 15-minute intervals the reading of the register is stamped through a typewriter ribbon upon a moving paper tape. Readings are taken for about 8 hours, so as to count at least 1000 alphas for each sample.

A background run is made of the disc in the chamber prior to measuring rock samples. A chamber background is also run at intervals by covering the sample disc with an inactive absorber, such as a sheet of paper, which absorbs all alpha particles emitted by the mounting disc itself. Background counts are subtracted from the alphas counted for a rock sample. Duplicate runs usually differ by less than 15 per cent.

The calibration of the ionization chamber for alpha-particle counting is based upon the calculations of Evans (1934), Finney and Evans (1935), and Evans and Goodman (1944). Standard rock samples similar to those used in calibrating beta counters are used as internal standards for the uranium and thorium series. The method is also useful in checking the active composition of the standard preparations used for calibration purposes.

For certain particularly interesting samples, separate radium (and hence uranium) determinations have been made using the direct fusion method. By use of the (1) beta particles from uranium, thorium, and potassium, (2) alpha particles from uranium and thorium, and (3) a separate measurement of the radium content, the concentration of each of the three active sources can be determined as indicated in the following section.

RESULTS

Through the co-operation of The Pure Oil Company a number of cuttings from wells drilled in the Seminole, Oklahoma, district were obtained. These samples were taken from the Mississippian, Devonian, Silurian, and Ordovician formations. The beta activity of the black shales in some instances amounts to more than 10 times the average activity of sedimentary rocks. The Chattanooga black shale (Woodford shale) displayed the greatest amount of total beta activity. This observation agrees with the outstanding activity of this material observed in gamma-ray logs (Green and Fearon, 1940). The two wells from which cuttings were taken showed good correlation on the basis of total activity of all samples. The Simpson sand was notably inactive, although oil taken from this sand contained radioactive material.

Another suite of samples was obtained from Pure No. 3 Gingrich, Osceola County, Michigan. Beta-ray and alpha-ray activities were obtained from a depth of 1600 feet down to a depth of 3200 feet and have been plotted against the geologic formations (Fig. 10).

In research on the origin of petroleum and the use of radioactive indicators for exploration purposes, it is desirable to know the locus of the radioactivity in the sediments and sedimentary rocks (Sheppard, 1944). Sandstones appear to have the bulk of their radioactivity associated with the heavy-mineral content (Clark and Botset, 1932). In the log of the Pure No. 3 Gingrich well, total beta activity apparently correlates with the percentage of black shale. Following this observation an attempt was made to determine the nature of the black shales. Preliminary examination indicated that the black material is carbonaceous organic matter. Hence limestones and dolomites, which have little activity when pure, may show a significant activity if their organic or shale content is appreciable.

The Antrim formation was selected for intensive study. About 200 grams of cuttings from 2800 to 2823 feet were dry ground, screened through Tyler sieves, and the total beta activity of each size analysis was measured. The results are shown in Table 1. The significance of these observations is the nearly 50 per cent increase in beta activity for the minus 200 mesh fraction.

Ideally, the sample should be of the original intrinsic particle size of the shale body. Practically, this condition is difficult to realize. Only one grinding was employed so that the finest particles would not be reduced below their original sizes. Without thorough washing of the cuttings after grinding, a considerable fraction of the finer sizes remained attached to the larger particles, preventing complete recovery of very fine fractions. However, the weight of fine particles in the larger fractions is so small that their contribution to the activity of these sizes may be neglected. The principal disadvantage of this method of separation is that the recovery of size fractions approaching those of the intrinsic particle size is small. The material recovered from the 2800–2823-foot interval of well cuttings was insufficient for complete analysis.

Approximately 20 grams of minus 200 mesh were treated by a sedimentation process for further division into size fractions. By comparison with established

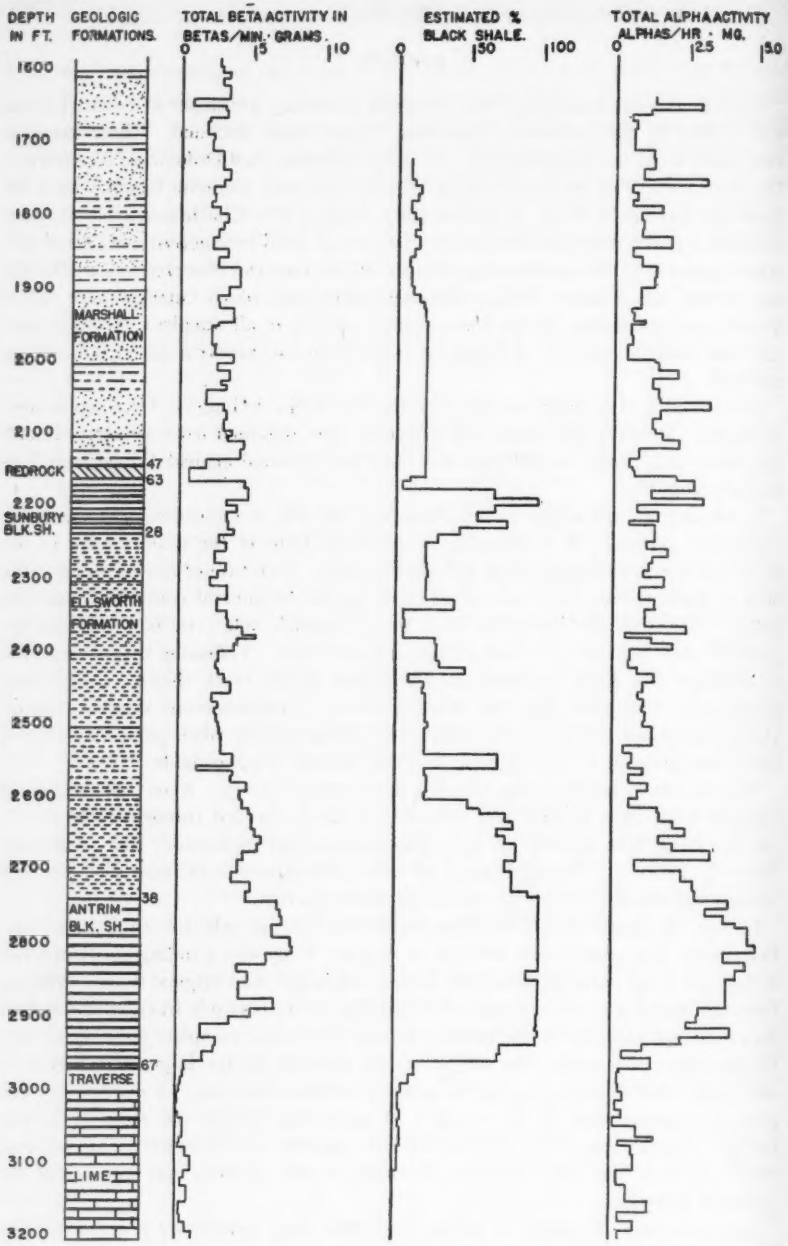

FIGURE 10.—*Log of total beta activity, alpha activity, and per cent black shale*

techniques it was found that all particles remaining after the entire minus 200 mesh sample had settled through 6 cm. water for 24 hours would be of 1 micron size or smaller. To accomplish this division into fine fractions the minus 200 mesh sample was dispersed in a 2 per cent aqueous solution of ammonium hydroxide, violently agitated for several minutes, and allowed to settle. After 24 hours the upper 6 cms.

TABLE 1.—*Total beta activity of Antrim shale by size grades*

2800 ft.–2828 ft. depth		
Screen Mesh		Equivalent activity Beta counts per minute per gram
On	Pass	
28	20	8.78
35	28	7.75
48	35	8.35
65	48	9.05
100	65	8.90
150	100	9.53
200	150	10.58
	200	13.20

of the dispersion were syphoned off. One per cent hydrochloric acid caused the particles to flocculate. This process was repeated 10 times to recover as much of each size fraction as possible. After sedimentation the clear supernatant liquid was removed and the balance evaporated to dryness. Thirty days later, when the radon had come to equilibrium, the sample was measured for total beta activity, carbon, hydrogen, and loss of weight upon ignition. To obtain sufficient material for all these analyses a further section of the Antrim was similarly treated, that from 2738 to 2760 feet, all 100 per cent black shale.

Since the distribution of radioactivity showed good correlation with particle size and per cent of black shale in representative cuttings, quantitative analyses were made of selected samples for carbon and hydrogen. The standard semimicro technique outlined by Niederl and Pregle was used. This method is one of dry combustion, wherein a sample is burned in an atmosphere of pure oxygen. The carbon dioxide and water vapor are collected separately by selective absorption. From 0.1 to 0.3 gram of sample are ground and placed in a sample boat, then weighed before combustion. The combustion products pass over copper-oxide gauze, silver wire, and platinized asbestos. Dehydrite is employed as a water absorbent, and Ascarite as a carbon dioxide absorbent. Oxygen flows through the combustion train, over the heated sample and catalyst. After 30 to 60 minutes of combustion the absorption tubes and the sample both are again weighed. The percentage loss of the sample always exceeds the total loss of carbon and hydrogen and presumably comes from undetermined components such as nitrogen, sulphur, organic water, and inorganic water.

It is assumed that organic matter is proportional to organic carbon (Trask, 1932). The dry-combustion method has the advantage of being independent of the carbonate content.

A similar series of determinations was made for selected well samples which repre-

sent distinct types of sedimentary environment. The selection of these samples was based on the detailed lithologic examination of well cuttings previously reported and embraces samples from 2144 to 2158 feet (Coldwater red rock), 2158 to 2162 (75 per cent limestone, 15 per cent green shale), 2163 to 2172 (Sunbury formation, 95 per cent dark clay to black shale), 2500 to 2510 (light-gray to greenish shale), 3048 to 3062 (95 per cent light-gray, crystalline limestone, Traverse lime).

Measurements were made of the total beta activity, radium content, total alpha activity, potassium content, carbon and hydrogen content, and loss of weight upon ignition. Thorium content was computed from the total activity and the radium content. Duplicate runs were made in all instances.

When the observations on selected samples from Pure No. 3 Gingrich well and those on the series of standard rocks had been compiled, it became evident that the method proposed for determination of each of the three radioactive constituents left something to be desired. In the first place the observed beta activity for many highly active rock samples was not sufficient to account for the sum of the beta activity expected from each of the constituents. In the standard rocks, potassium content was known exactly from chemical determinations, and the uranium content had been agreed upon by several independent workers. The conclusion was inescapable that the determination of thorium by differences from the total alpha activity, the total beta activity, and separate radium determinations did not yield satisfactory figures for highly active rocks such as granites and organic black shales.

The most probable source of error is in the high emanating power of the more active rocks. Evidently if any substantial portion of radon and thoron escapes from the rocks during the observations, iusufficient total alpha activity and total beta activity will be observed. The proper procedure is to confine such rock samples for 30 days after they have been prepared for observation. This precaution was not taken until quite late in the course of the research when there was insufficient time to prepare and store all the rocks measured. The error in total alpha activity is probably much greater than that in total beta activity, particularly in igneous rocks which are relatively coarse. The black shales have exceedingly high emanating power, even when not ground to small sizes. Evidently the permeability of these shales to radon and thoron is relatively large.

In an attempt to distribute the error caused by emanating power between the measurements of total alpha activity and total beta activity, the following considerations were employed: The series of standard radioactive rocks were measured for total alpha activity. These measurements involved grinding the rock samples to minus 10 micra, thus releasing substantial quantities of radon and thoron. Next, the total beta activity of the unground coarse samples was measured. After the beta-ray counters had been calibrated, the beta contribution was computed from potassium and from uranium for each of these standard rocks by reference to their known potassium and uranium concentrations. The sum of these two beta activities subtracted from the total observed beta activity in the calibrated counter gives the beta activity to be expected from thorium. By reference to the thorium calibration of the counter, the thorium concentration is obtained. A simple computation involving Figure 8 then yields the alpha activity to be expected from the known

uranium and computed thorium content. Sometimes this method gives a fairly satisfactory idea of the relative concentrations of uranium, thorium, and potassium in these rocks; in other instances the results are not satisfactory, and further work must be done.

INTERPRETATION OF RESULTS

Although absolute values for the radioactive content of all the samples cannot be given because of the complication caused by loss of emanation, the relative values are reliable in almost all cases. For the stored samples and those of low emanating power, the observed activities represent the true values within the experimental uncertainties dictated by the statistical emission of the radiations measured. With these reservations a number of interesting conclusions can be drawn from the experimental results. Stratigraphic relationships are evident from the correlations shown in the logs of Figure 10. In addition a number of other relationships were observed. Almost invariably high emanating power is associated with high radioactivity. Whether the rock is igneous or sedimentary, samples having more than 10^{-12} g. Ra/g. tend to lose a significant fraction of the equilibrium amount of radon and thoron. Some granites lose over 50 per cent. Basic rocks, which range in radium content from .009 to .60 $\times$ 10^{-12} g. Ra/g., seem to retain practically all their emanation. Organic shales, possessing upwards of 20 $\times$ 10^{-12} g. Ra/g., even exceed the active granites in emanating power. One sample of black shale lost 75 per cent.

Rocks of high potassium content may be expected to have high uranium content. For igneous rocks this association is shown in Figure 13. An interesting exception to this relationship is the Milford granite which may not be of primary igneous origin. Similar quantitative relationships between potassium and uranium were also observed in sedimentary rocks.

A number of significant relationships were found to hold for all types of sediments examined. Organic matter correlates with total alpha activity, total beta activity, the concentrations of uranium, thorium, and potassium, the thorium/uranium ratio, and decrease in particle size. For Paleozoic black shales, some of these correlations show linear relationships. The excellent agreement of data on uranium content, thorium/uranium ratio (Fig. 11) and particle size (Fig. 12) suggests the action of selective agencies which account for the observed distribution of these factors.

Evans, Kip, and Moberg (1938) have observed the correlation between radium content and particle size in ocean sediments. Evans and Williams (1935) have noted a rough correlation between radium content and potassium in Lassen lavas. Evans (1934) found the emanating power of carnotite to exceed 35 per cent. Trask (1932) observed that organic content of recent sediments increases in the smaller size fractions. Revelle (1936) has noted a correlation between the radium content and the organic siliceous remains in sediments and concludes that dissolved radium is extracted from the water by the diatoms and Radiolaria.

From a broad viewpoint it may be concluded that there are three principal loci of radioactivity in sedimentary rocks. The first is in association with heavy minerals—thorium and uranium—in sands and sandstones. These deposits exhibit

high Th/U ratios and generally contain little potassium. Cementing materials of these rocks, such as silica and calcite, usually exhibit low activity. If a substantial amount of clay, shale, or organic matter is incorporated in sandstone, additional

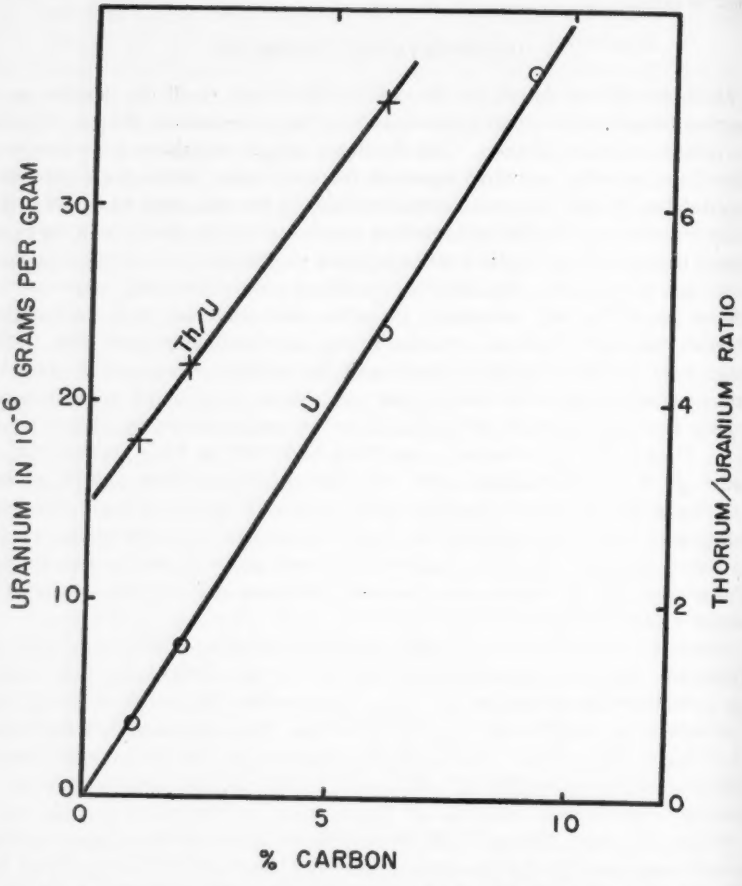

FIGURE 11.—*Uranium content, thorium/uranium ratio as related to carbon content in sedimentary rocks*

activity will be found therein. Arkose sands are generally not so active as their granitic antecedents. Even though the original feldspars may have contained potassium, their decomposition has generally released much of it. Further work is needed on the activity of arkose and "granitized" rocks.

A second source of activity is found in K^{40}, the active isotope of potassium. The highest concentrations of potassium are in sedimentary deposits of evaporites including sylvite, carnallite, kainite, and polyhalite. Certain oil-field brines contain appreciable potassium (Mestier, 1943). Sediments containing clastic fragments of

muscovite, phlogopite, biotite, lepidolite, sericite, and the alteration products of these and other potassium-bearing minerals will exhibit beta activity in proportion to their potassium content. The most widespread occurrence of potassium is in clays and shales which may contain up to 6.5 per cent. This amount exceeds the theoreti-

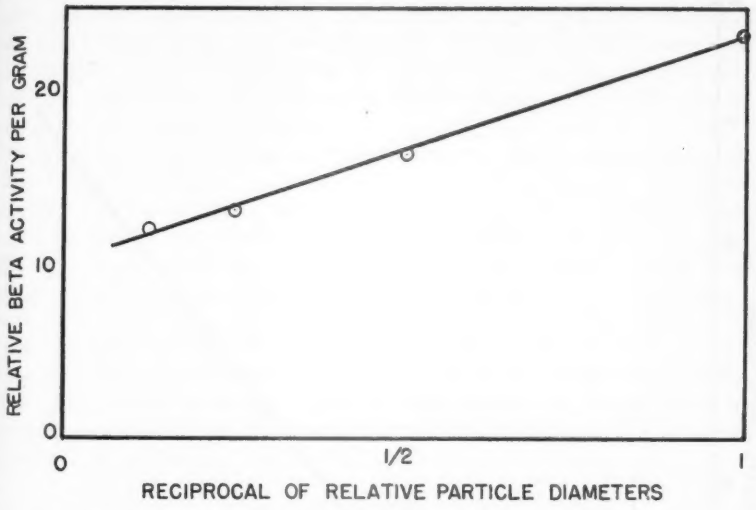

FIGURE 12.—*Relative beta activity as related to particle size in black shales*

cal potassium content of a shale composed entirely of potassium-bearing clay minerals (illite or hydromica) and suggests the presence of potassium in other chemical associations. The structure of clay minerals is such that considerable potassium may be adsorbed to the edges and corners of the crystal plates, the amount depending upon the particle size distribution. Hendricks (1940) has shown that about 80 per cent of the exchange ions of montmorillonite are on basal planes and surfaces and that the remainder are on the edges of the flakes. Endell and Vageler (1932) report that much of the base-exchange capacity of illite is on flake edges. Many cations (*e.g.*, potassium) may be held between the basal planes of illite and hence are not replaceable.

Enough is known of the behavior of potassium in the colloidal environment to substantiate these observations. However, it is not generally known that certain members of the uranium and thorium series are also colloidal in aqueous dispersions. Hahn (1936), Paneth (1928), Fajans and Beer (1913), and Freundlich and Rona (1920) have reported related researches. Even below the limits of solubility many of these active elements favor colloidal dispersions to molecular solutions. If only an incipient tendency exists to enter the colloidal phase, the stability of such dispersions would be enhanced by the presence of other colloids such as clay minerals and organic matter. Ions will be present in the aqueous solution, some originated by radioactivity, others by dissociation. In the region of the electrokinetic potential

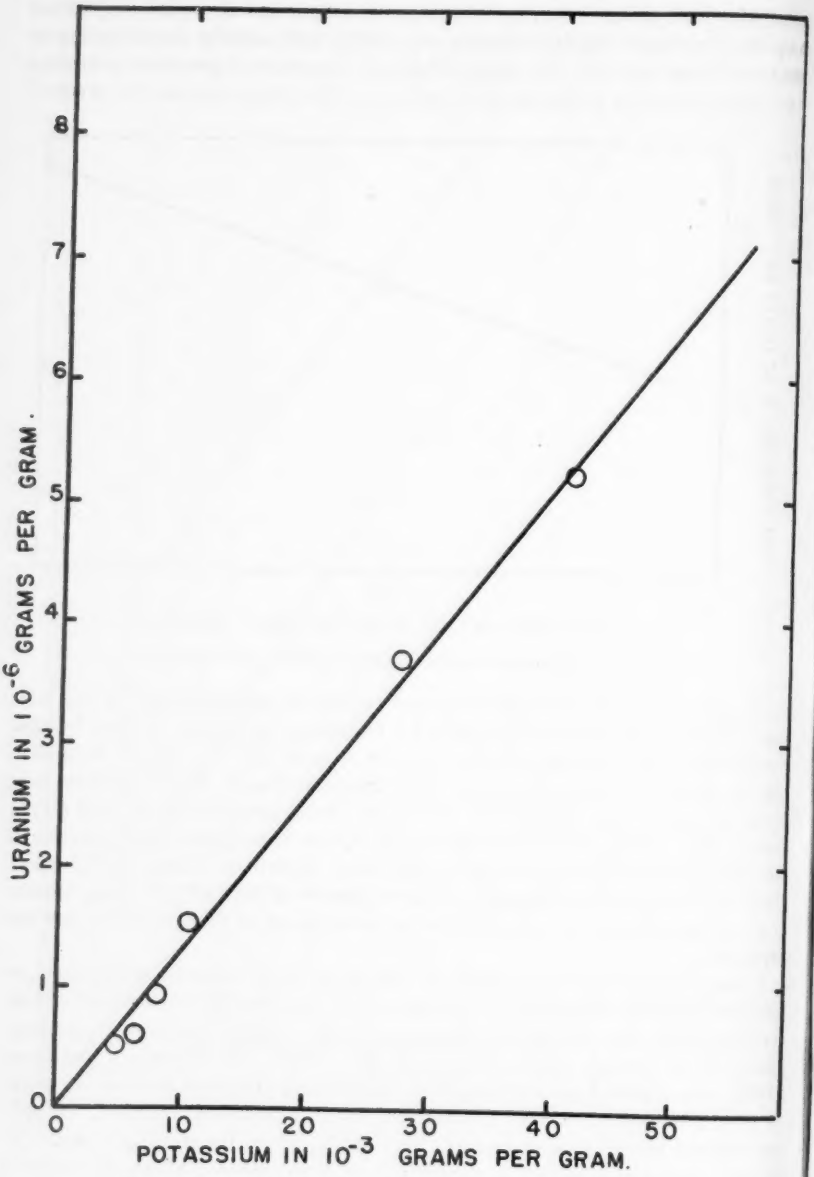

FIGURE 13.—*Relationship of uranium and potassium in igneous rocks*

on the face of clay minerals, these ions are in an electric field. Hauser 1939) observed the difference of potential to be of the order of 0.1 volt. Norton (1933) has found the thickness of water hulls on certain clay minerals to be about 3×10^{-5} cm. The thickness of the electrokinetic-potential region can scarcely be greater than that of water hulls. Consequently as a lower limit the corresponding electric intensity would be 3000 volts per cm. This gradient together with the mobility of common ions found in sea water is sufficient to neutralize the charge around the region involved. Cohesion of similarly affected particles would result in their sedimentation. Experiments with radium and x-rays have shown that sedimentation by these agencies is relatively common.

The third locus of radioactivity is in the uranium-series and thorium-series content of shales and clays, impure limestones and marls, shaly sandstones, and organic sediments. All these deposits have one common factor: At some stage in their depositional history the colloidal phase has been dominant. A pure, crystalline limestone or a pure, white quartz sand exhibits practically no measurable radioactivity. Those limestones which show appreciable activity also contain proportionate amounts of shale, organic matter, or other material which has once occupied the colloidal phase. Sandstones containing substantial quantities of shale or organic matter flocculated from a colloidal dispersion will show correspondingly higher activity than pure quartz sands.[2] Thus the distribution of the bulk of the radioactivity in sediments and sedimentary rocks appears to be the result of concentration in a colloidal environment.

CONCLUSION

During this research several hundred rock samples have been measured for total alpha activity and total beta activity. On selected well samples representing distinct types of sedimentary rocks, separate determinations have been made of potassium radon, carbon, and hydrogen content. If the total alpha activity and total beta activity are known, by correlation and interpolation of data from the selected samples the three radioactive constituents can be computed.

Because of the relatively high emanating power of the more active rocks, the full magnitude of alpha and beta activity can be determined only by measurements on samples which have been confined for at least 30 days. Since the implications of this situation were not realized until very late in the program of research, complete determinations could not be made for all samples. However, for calibration purposes enough samples were stored and measured to provide quantitative results.

Although considerable additional research needs to be done, the following conclusions have been established or substantiated:

(1) Rocks of high uranium and thorium content possess high emanating power.

(2) In primary igneous rocks and organic black shales, potassium and uranium content increase directly with one another.

(3) Organic black shales show excellent correlation of uranium content, organic matter, abundance of colloidal size grades, high thorium/uranium ratio. All these

[2] Pure quartz is so inactive that it may be used as a background material in counters.

correlations indicate possible genetic relationships in petroleum source beds and may have a bearing on one possible origin of oil.

(4) As indices of potential petroleum source beds, uranium content, total alpha activity, total beta activity, and thorium/uranium ratio are suggested as having great value. Goodman (1942) predicted the probable occurrence of high Th/U ratios in petroleum source beds. These measurements offer the first direct data in support of this theory.

(5) The technique developed in this research makes possible the rapid investigation of stratigraphic sequences related to the generation, migration, and accumulation of oil. For the first time, radioactivity measurements can be made within a few minutes on small quantities (1 to 10 grams) of ordinary terrestrial materials.

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